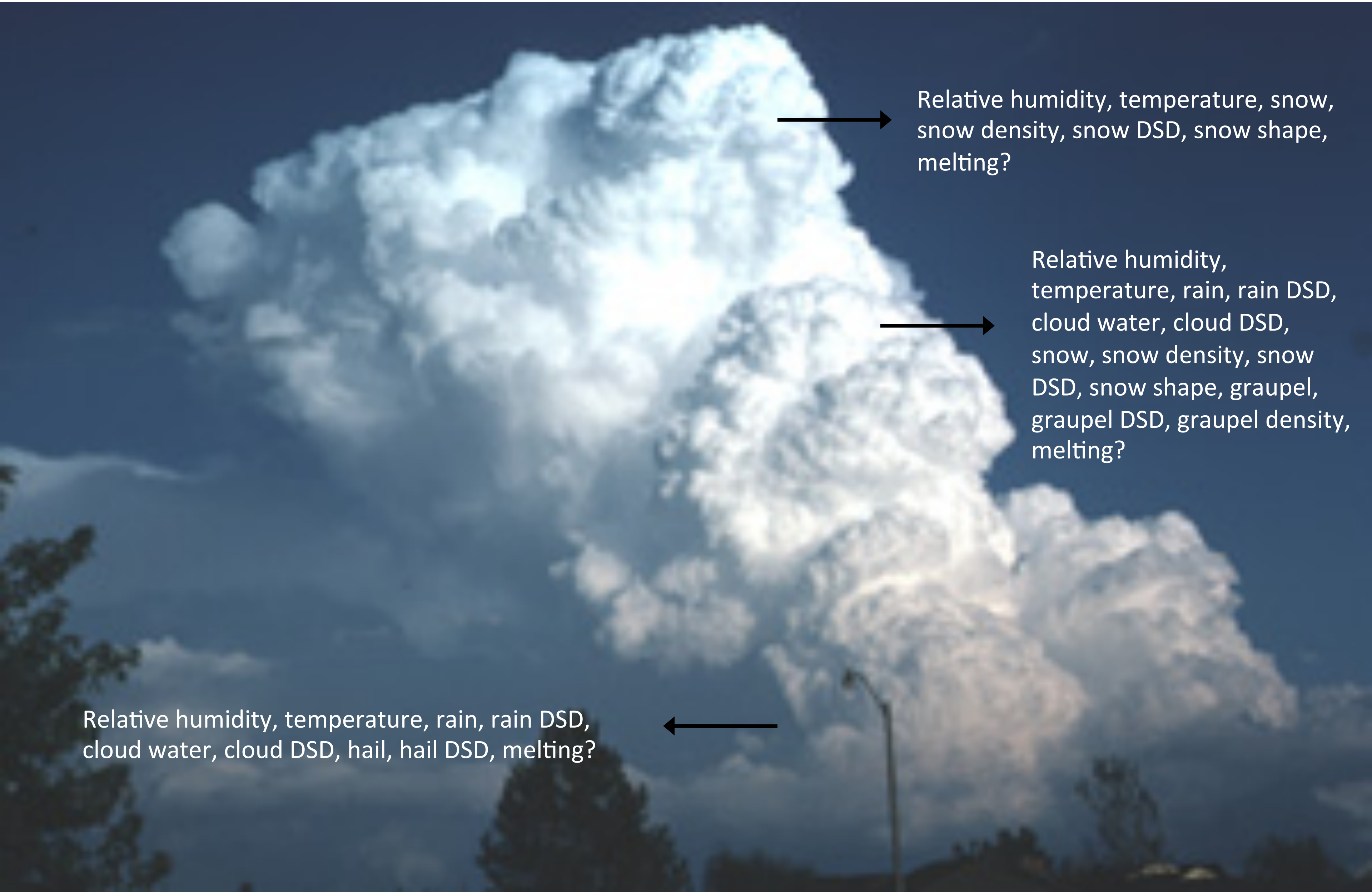
Observational Challenges and Uncertainties in Estimating Global Precipitation from Satellites

Wesley Berg

Colorado State University

Real Clouds are Complicated



Satellite Precipitation Sensors

- Visible/Infrared
  - Good: High spatial and temporal sampling.
  - Poor: Very limited information content (i.e. Cloud-top Temp) and substantial regime differences in relationship to precipitation.
  - Use: Primarily in high-resolution merged products (i.e. GPCP).
- Microwave Imagers (Window-channel Radiometers)
  - Good: Relationship between observed Tb and rainfall over oceans. Relatively good sampling due to wide swath and availability of multiple sensors extending back to 1987.
  - Poor: Over land relies on scattering signal due to high emissivity of and surface, which is poorly related to surface precip and misses warm rain. Relatively low spatial resolution.
  - Use: Basis for most ocean precipitation datasets due to combination of direct relationship between observed Tb and column water/ice along with decent sampling and overall availability.
- Microwave Sounders (Typically using water-vapor sounding channels)
  - Good: Coverage and insensitivity to land surface effects provides consistent estimates over land/ocean/ice (exception is very dry atmospheres at higher latitudes).
  - Poor: Sensitivity to light and/or shallow precipitation. Less information than imagers and retrievals are much less mature (no sounder channels on TRMM, but they will be on GPM core).
  - Use: Land and high latitude retrievals and to fill in between imager passes over ocean.
- Radar
  - Good: High information content including vertical structure and high spatial resolution. Provides by far the best satellite estimates over land.
  - Poor: Narrow swath and very limited sampling. Limited sensitivity to light rain (CloudSat sensitivity is opposite) and ice. Is very sensitive to changes in DSD (GPM has dual-frequency radars) and attenuation at high rain rates.
  - Use: To develop apriori database for microwave retrievals and investigate precipitation cloud physics.

GOES West Infrared Image

April 2, 2004

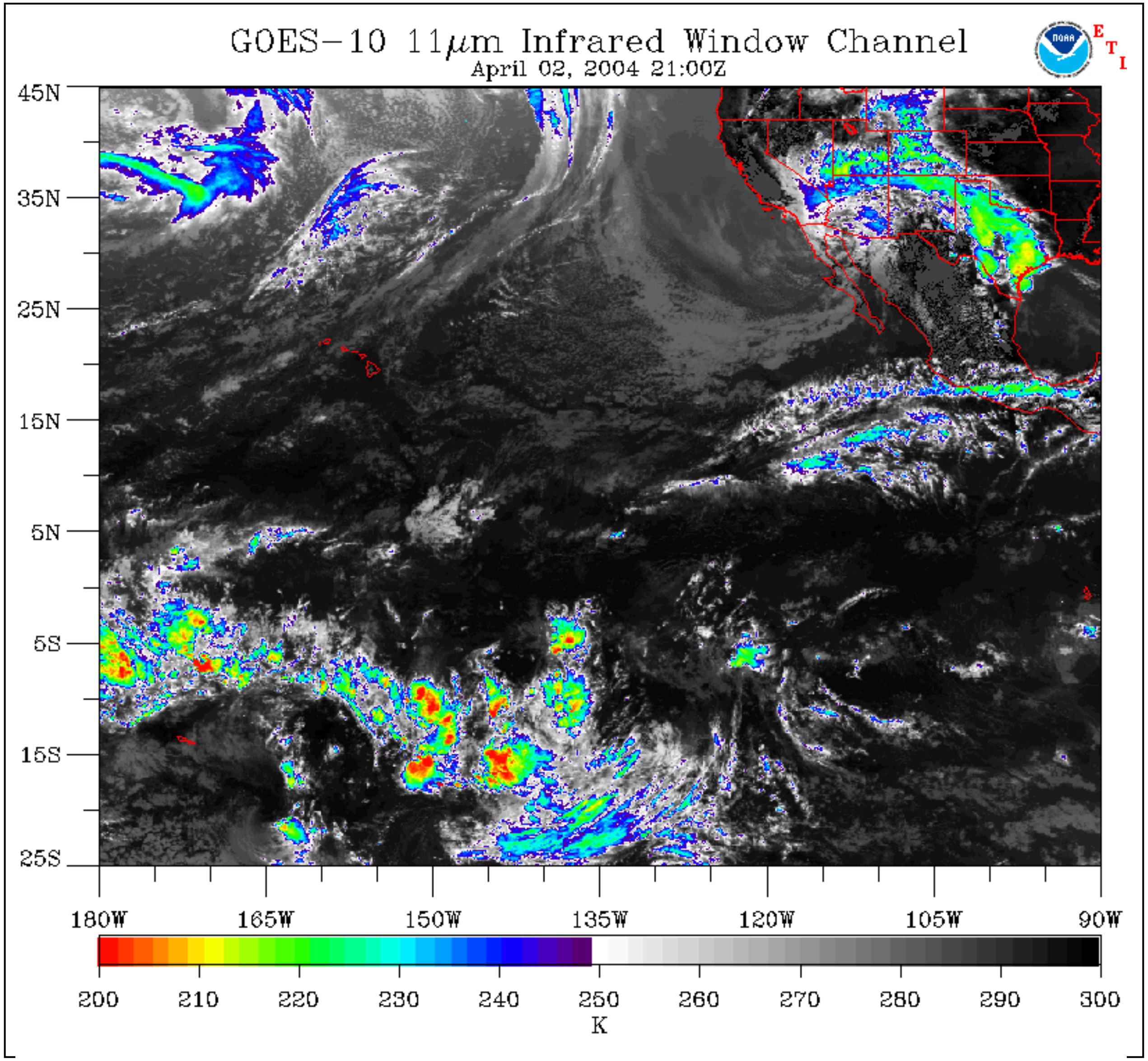
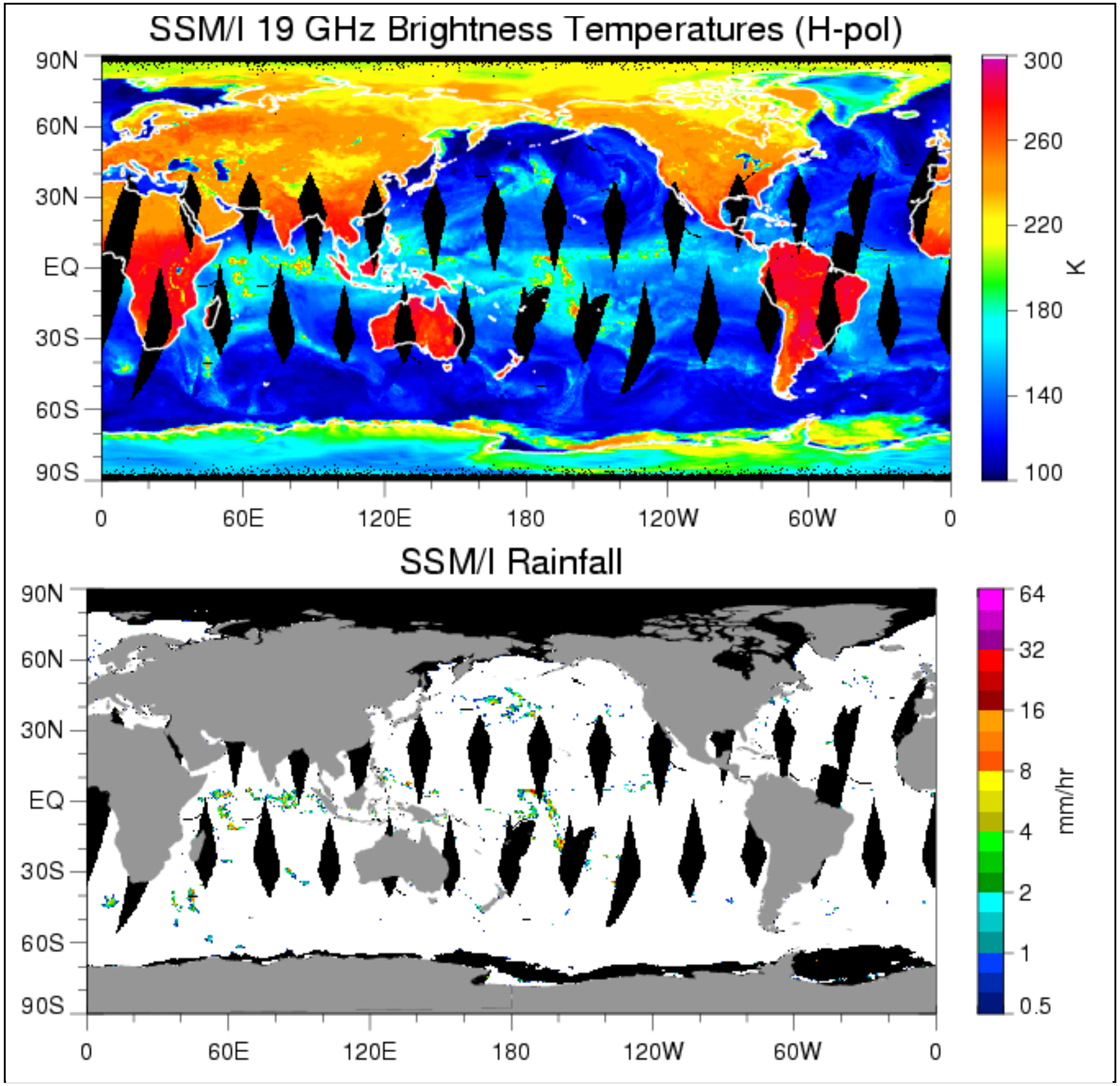


Image produced by NOAA/ETL

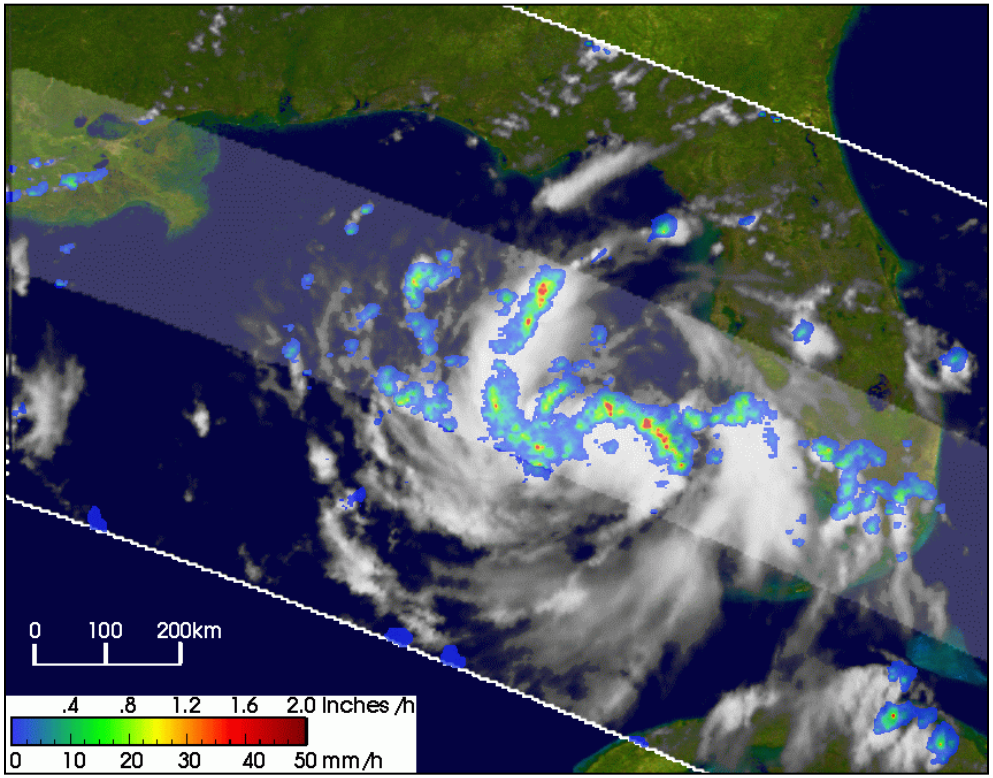
Passive Microwave (SSM/I)

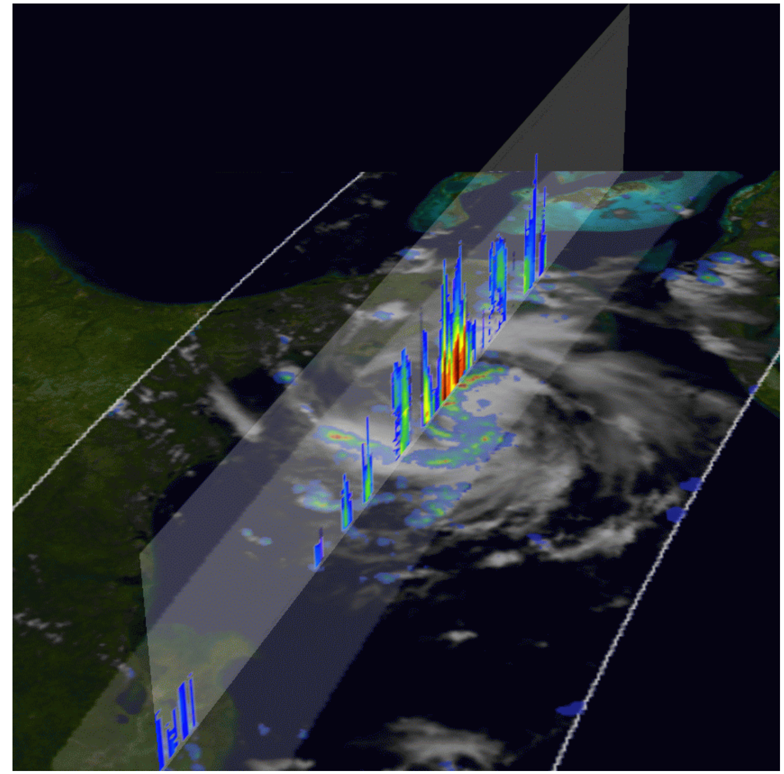
(January 1, 1995)



TRMM PR → Tropical Storm Erika

August 14, 2003



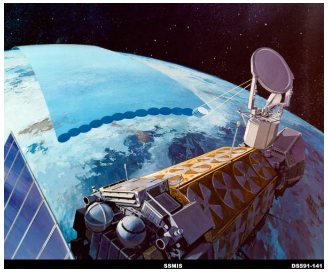


Images produced by Hal Pierce
NASA/GSFC

Key Precipitation Satellites/Sensors

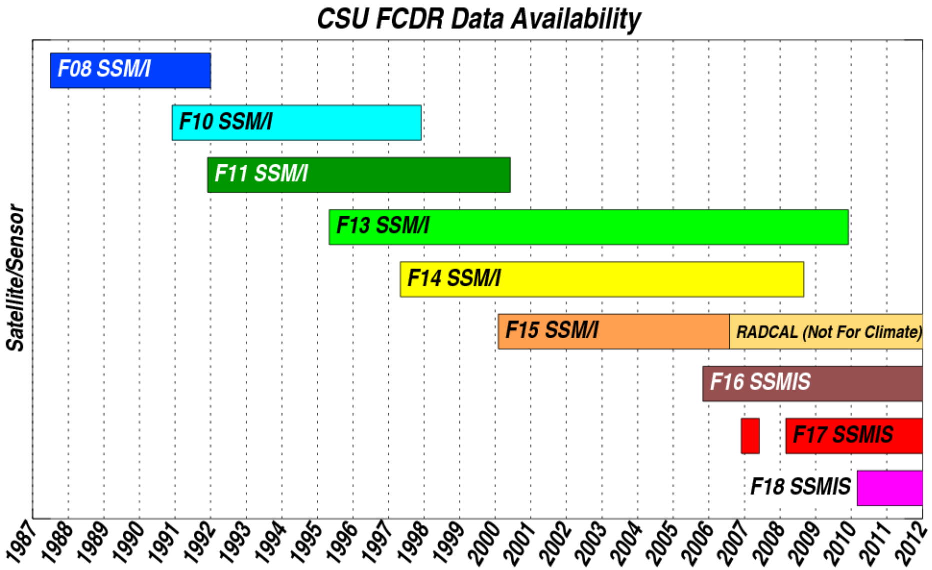
- Microwave Imagers
  - DMSP SSM/I and SSMIS (Basis for high quality long-term climate record over global oceans)
  - AMSR (ADEOS II), AMSR-E (EOS Aqua, Jun 2002 – Sep 2011), and AMSR2 (GCOM-W, Jun 2012 – Present
  - WindSat, MADRAS (Megha-Tropiques), MWRI (FY3B)
- TRMM
  - Launched in 1997 and with the exception of CERES all of the instruments are still operating.
  - Combination of microwave imager, precipitation radar, and Vis/IR.
  - First precipitation radar in space providing unprecedented observations over the tropics/subtropics (37S to 37N).
  - Has led to dramatic improvements in satellite precipitation estimation.
- CloudSat
  - Cloud radar sensitive to the onset of precipitation and light precip over oceans. Although very limited sampling due to nadir-only view provides complementary information to TRMM PR.
- GPM
  - Scheduled to be launched in February 2014.
  - 65 degree inclination orbit. Dual frequency Ka/Ku band radars with TMI like radiometer plus high frequency water vapor sounding channels.

SSM/I and SSMIS



- SSMI and SSMIS are polar-orbiting passive microwave radiometers flying aboard DMSP satellites
- 6 SSM/I sensors starting in 1987
  - F08, F10, F11, F13, F14 and F15
- 5 SSMIS sensors
  - F16, F17, F18 currently operating
  - F19 and F20 not yet launched
- Length of record makes these satellites important for climate

SSM/I: Special Sensor Microwave/Imager
SSMIS: Special Sensor Microwave Imager/Sounder



SSM/I has 7 Channels:
19 V&H, 22 V, 37 V&H, 85 V&H GHz
SSMIS has 24 Channels
7 correspond to SSM/I:
19 V&H, 22 V, 37 V&H, 91 V&H GHz

Tropical Rainfall Measuring Mission (TRMM)

TRMM Sensors

Nov. 1997 launch, 35° inclination; 402 km

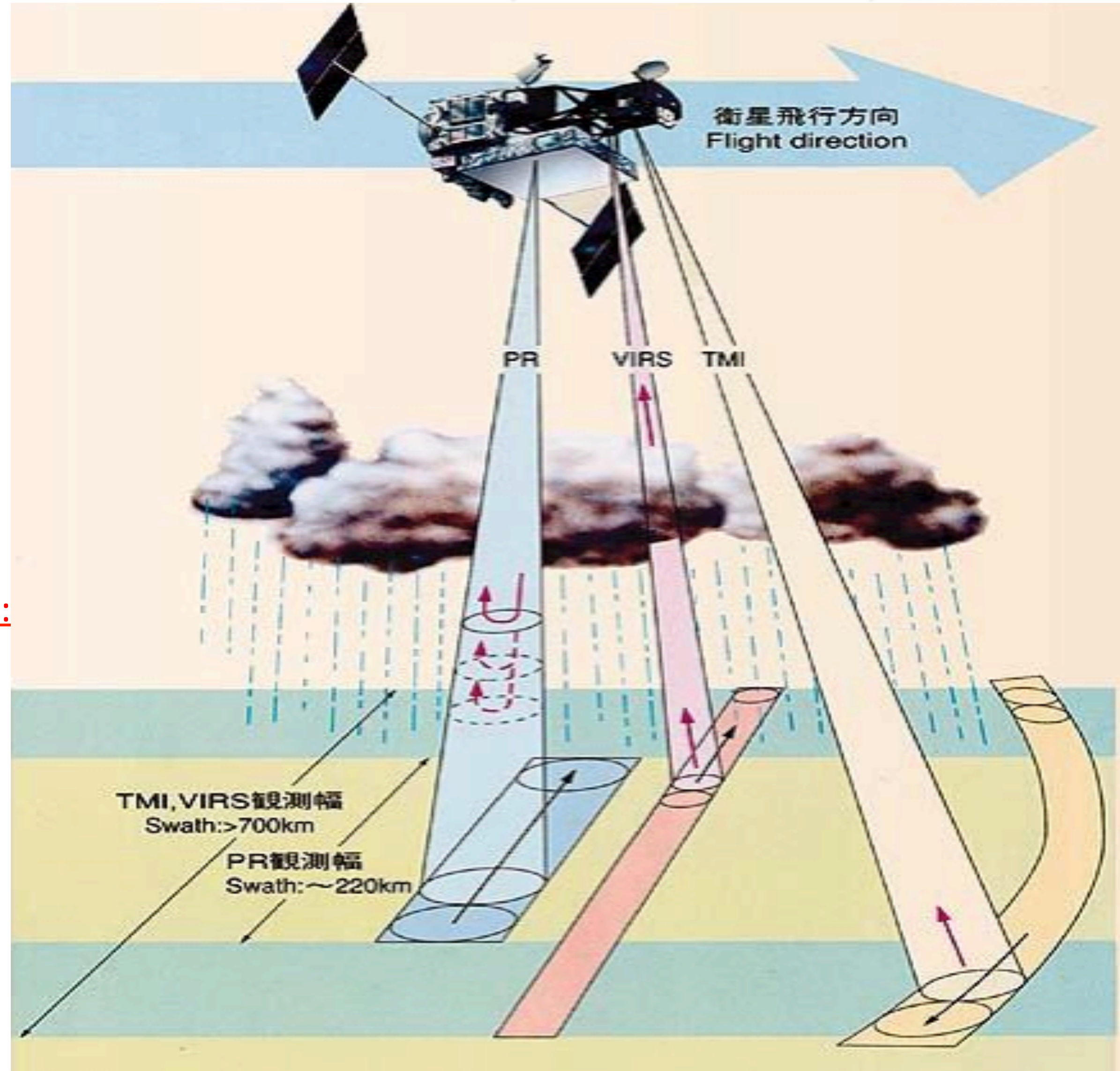
Precipitation radar (PR):
- 13.8 GHz
- 4.3 km footprint
- 0.25 km vertical res.
- 215 km swath

Microwave radiometer (TMI):
- 10.7, 19.3, 21.3, 37.0
- 85.5 GHz (dual polarized
- except for 21.3 V-only)
- 10x7 km FOV at 37 GHz
- 760 km swath

Visible/infrared radiometer (VIRS):
- 0.63, 1.61, 3.75, 10.8, and 12 :m
- at 2.2 km resolution

Lightning Imaging Sensor (LIS)

Cloud & Earth Radiant
Energy System (CERES)

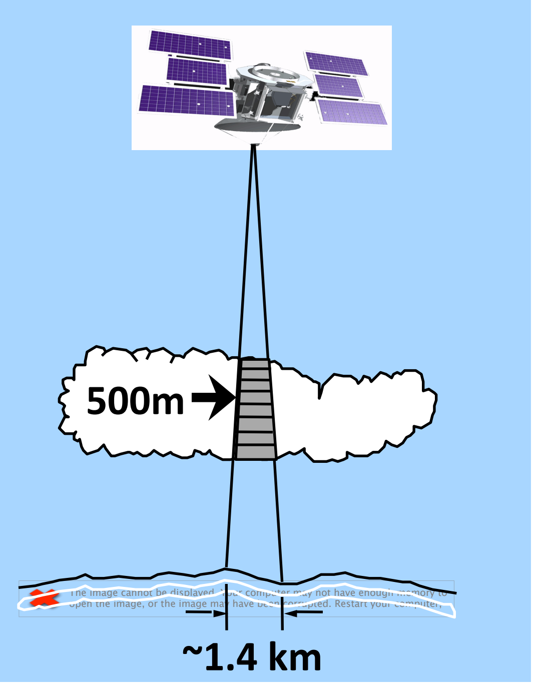


The CloudSat Mission

Primary Objective: To provide, from space, the first global survey of cloud profiles and cloud physical properties, with seasonal and geographical variations needed to evaluate the way clouds are parameterized in global models, thereby contributing to weather predictions, climate and the cloud-climate feedback problem.

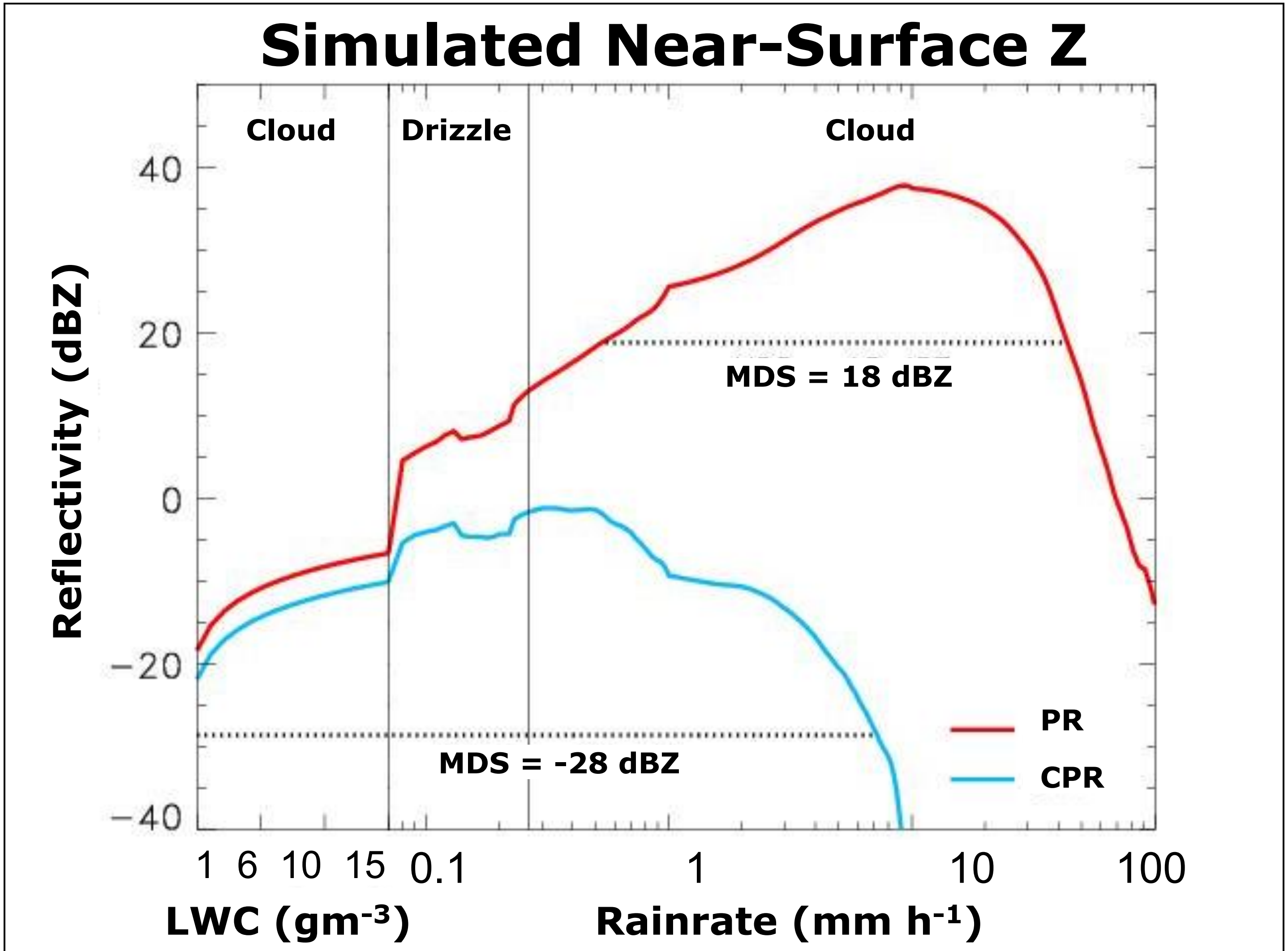
The Cloud Profiling Radar

- Nadir pointing, 94 GHz radar
- 3.3μs pulse → 500m vertical res.
- 1.4 km horizontal res.
- Sensitivity ~ -28 dBZ
- Dynamic Range: 80 dB
- Antenna Diameter: 1.85 m
- Mass: 250 kg
- Power: 322 W



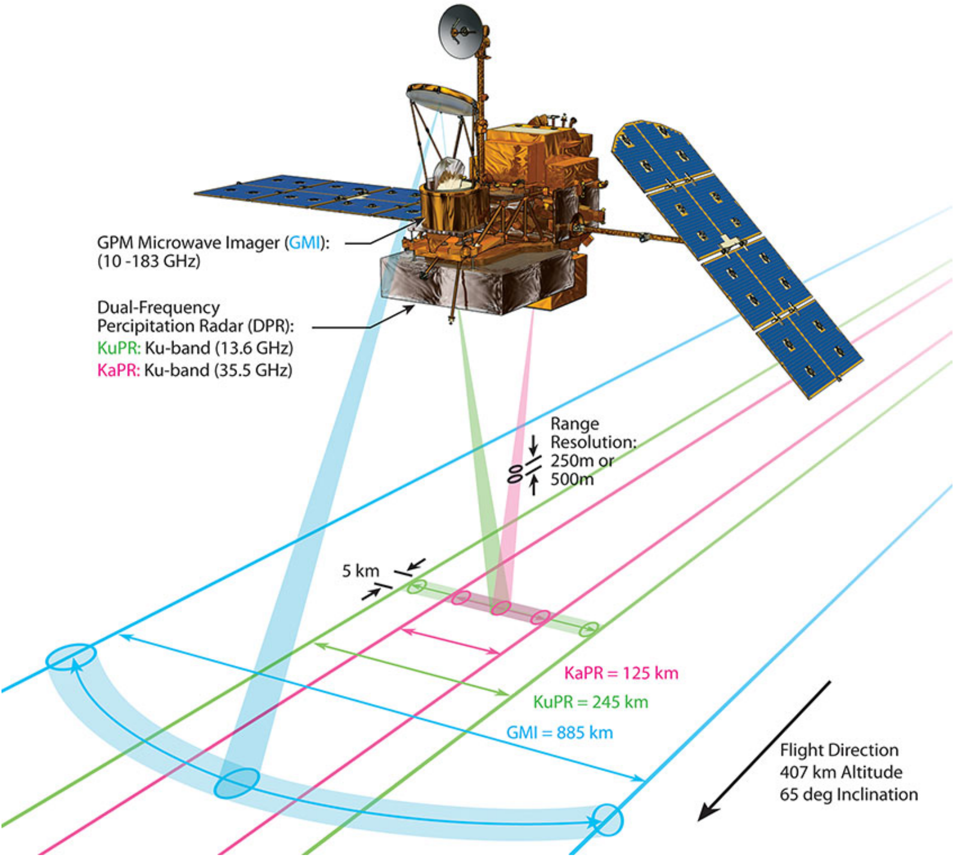
Differences in Radar Sensitivity

TRMM PR (13.8 GHz) vs. CloudSat (94 GHz)

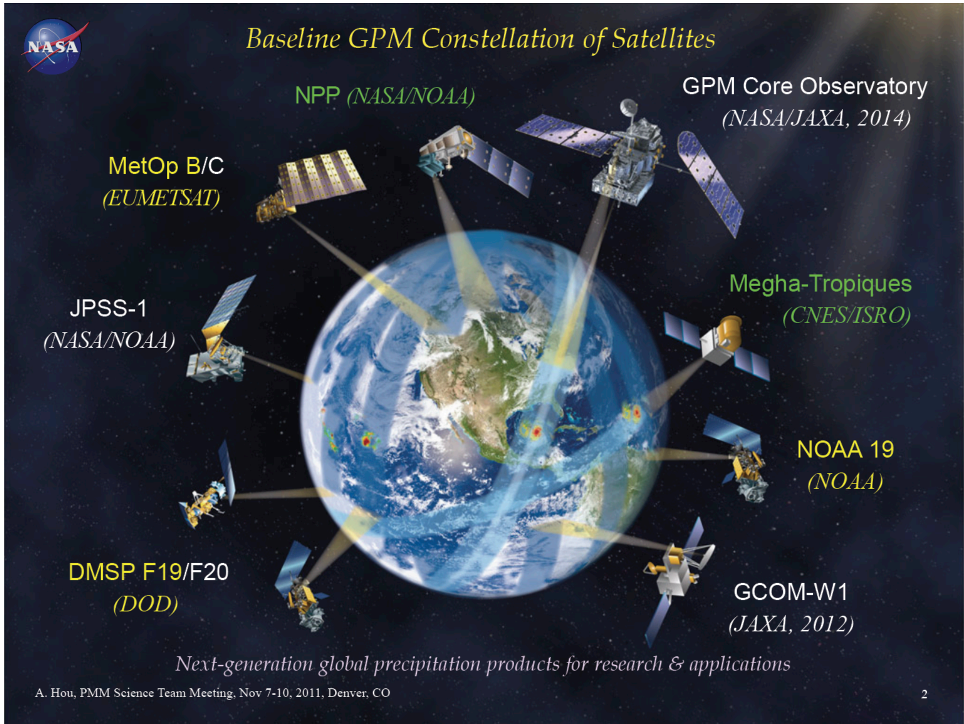


Courtesy Tristan L'Ecuyer

The GPM Concept



Constellation radiometers are contributed by any agency to produce the frequent sampling required by many applications.



NASA/JAXA contribute Core Satellite

Climate Analysis

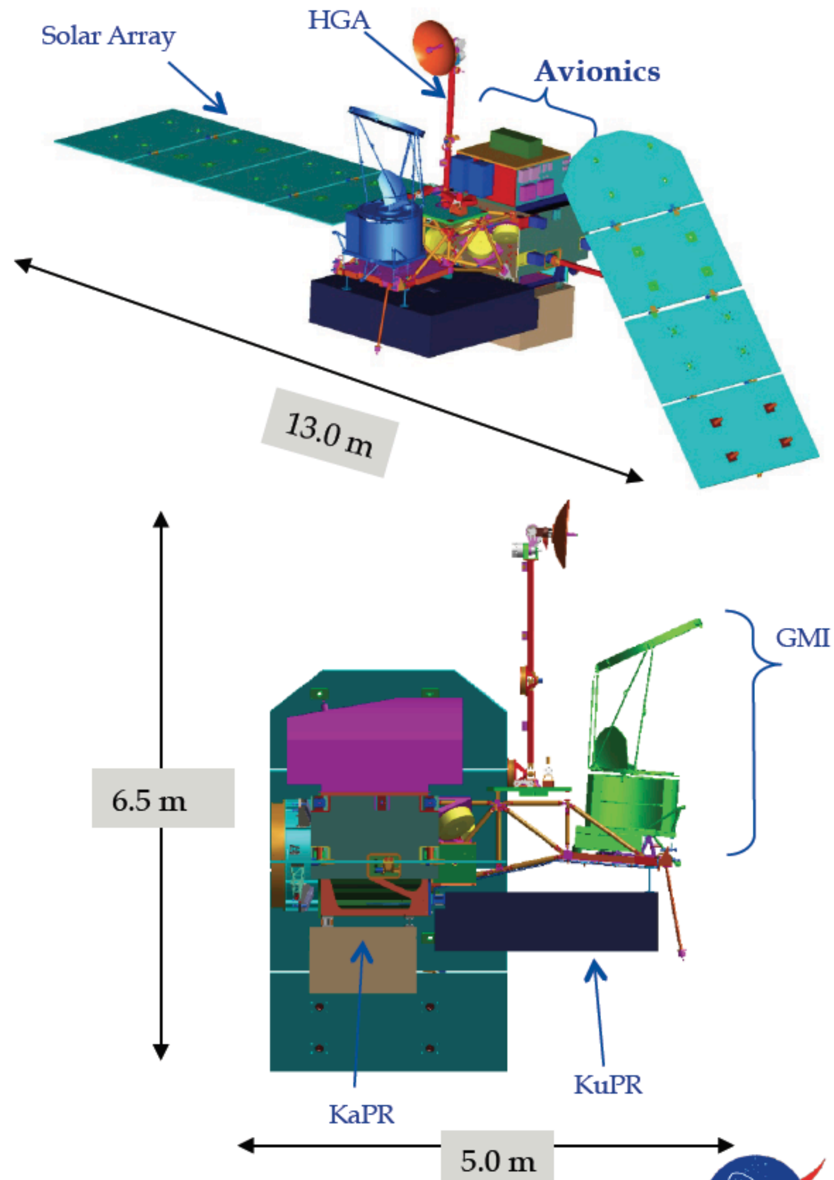
Precipitation Physics

GPM Core Satellite carries:

- *a dual-frequency radar &*
- *a passive microwave imager with high frequency capabilities*

GPM Core Observatory

- **Orbit: 407 km; 65 degree inclination**
- **3 year design life with 5 years propellant**
- **Controlled re-entry at end of operational life**
- **GPM Microwave Imager (GMI) : Conically Scanned Radiometer (Ball Aerospace)**
  - 10.6,18.7,23.8,36.5,89,166 & 183 GHz
- **Dual-Frequency Precipitation Radar (DPR = KuPR + KaPR): JAXA**
  - 13.6,35.5 GHz
- **Spacecraft bus: GSFC in-house design**
  - Aluminum and Composite
  - Modular, fully-redundant avionics
  - Steerable high-gain antenna on dual-hinged boom
  - Solar arrays track the sun
  - 12 thrusters (4 forward, 8 aft)
  - 240 Amp-hour Lithium Ion Battery
  - Size: 13.0m x 6.5m x 5.0m
  - Mass: 3850 kg
  - Power: ~1950W
  - Data Rate:~ 300 Kbs (with onboard storage)



Sensor Differences

Issues for Climate

- Sampling issues
  - Spatial Resolution
  - Coverage
    - Swath width
    - Land/Ocean
    - Orbit inclination (global/tropical)
  - Temporal Sampling

- Information content
  - Physical relationship to rainfall
  - Sensitivity
    - IR → Cloud top temperature
    - Passive microwave → Column integrated water/ice
    - TRMM Radar → vertical profile (250m res.), ~17dBZ minimum detectable signal

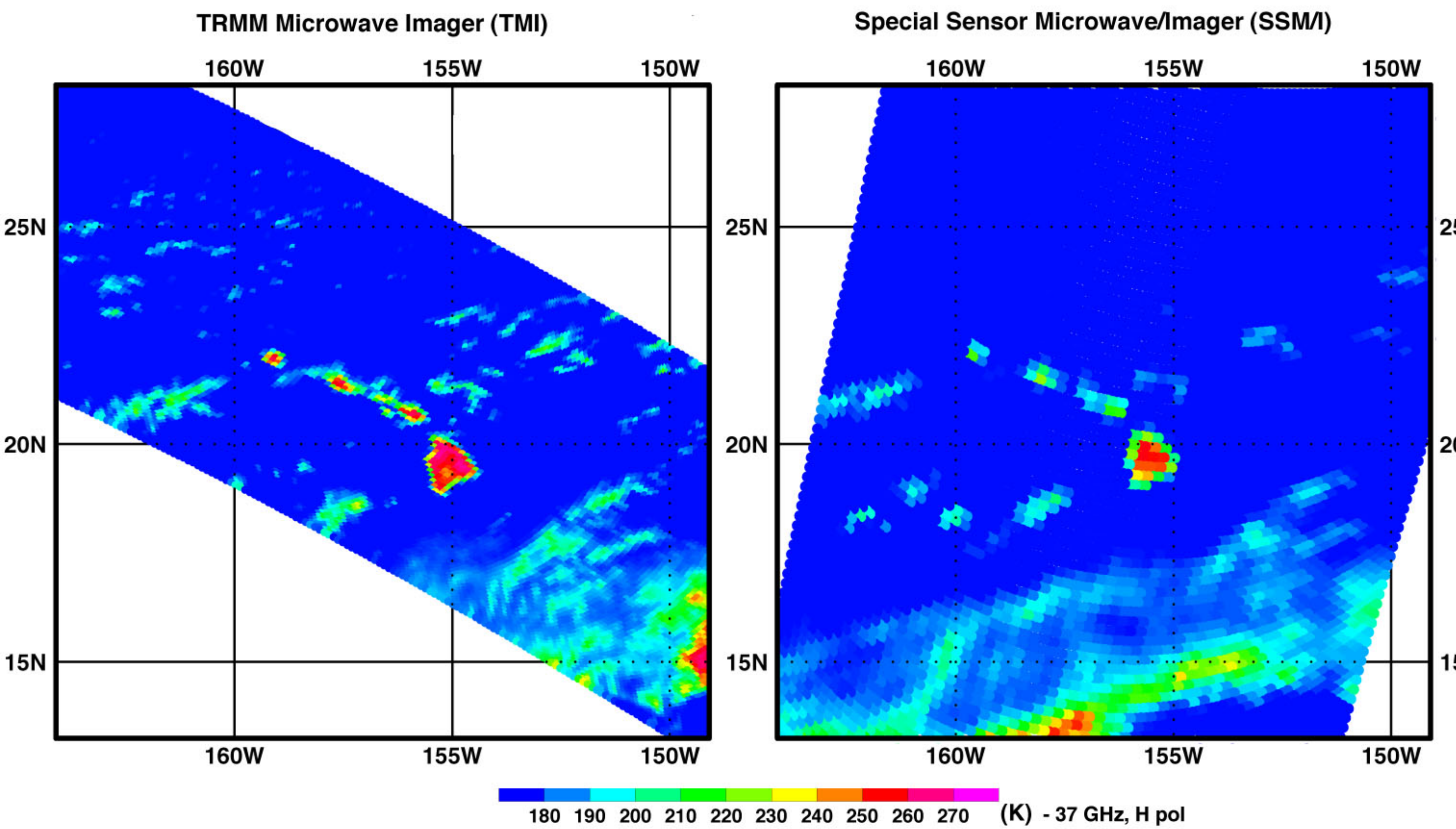
TRMM TMI vs. SSM/I

Improved Spatial Resolution

Tropical Rainfall Measuring Mission (TRMM)

16:33z, 2nd December 1997, centered on 156.6W, 20.75N, Hawaii

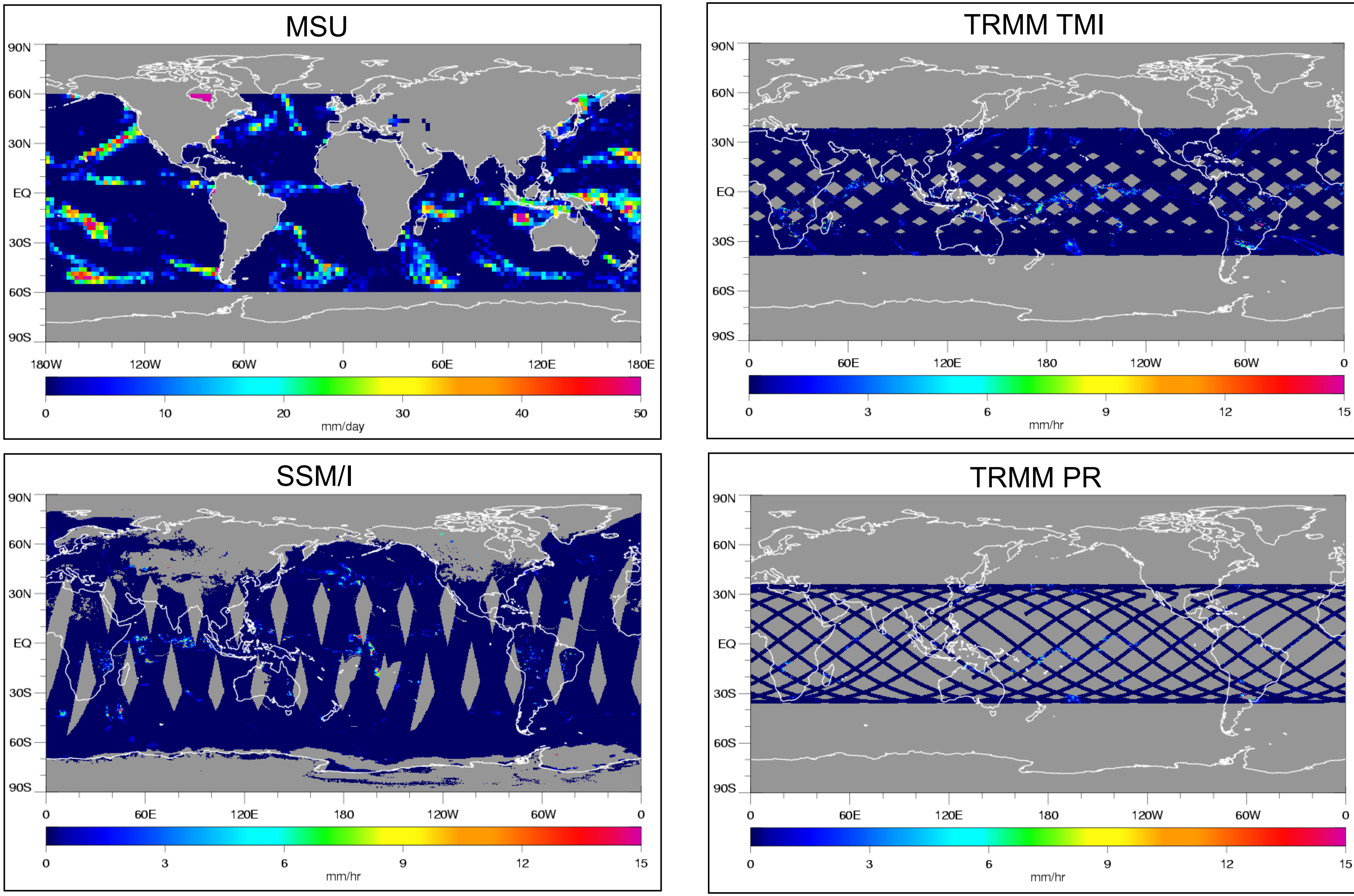
NASDA
NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN
NASA



Simultaneous images of TRMM Microwave Imager (TMI) and Special Sensor Microwave/Imager (SSM/I). The greater spatial resolution of TMI will allow higher quality rainfall estimates to be made.

Dataset Differences → Sampling Issues

1-Day Global Coverage



Satellite Observing Times

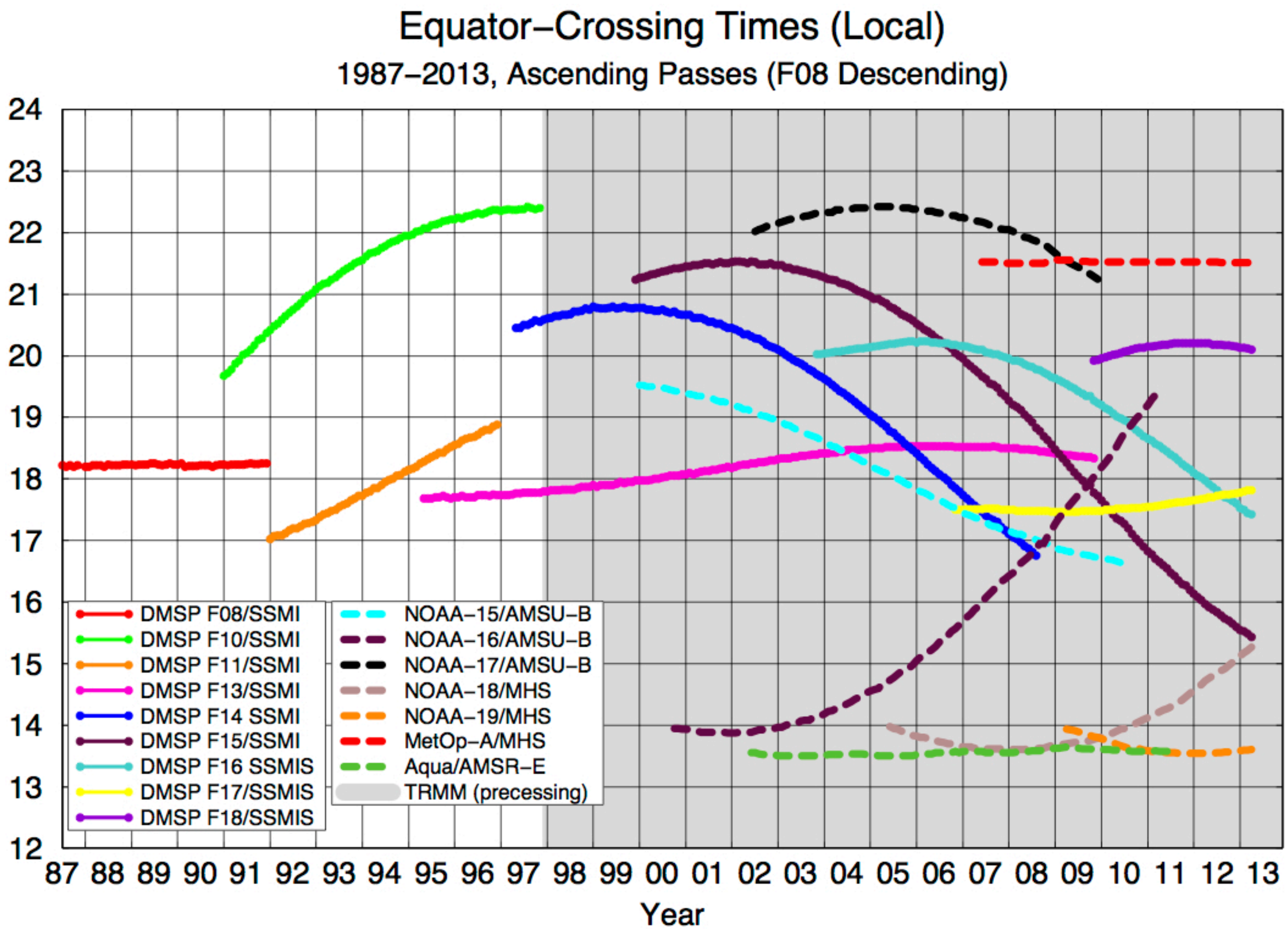
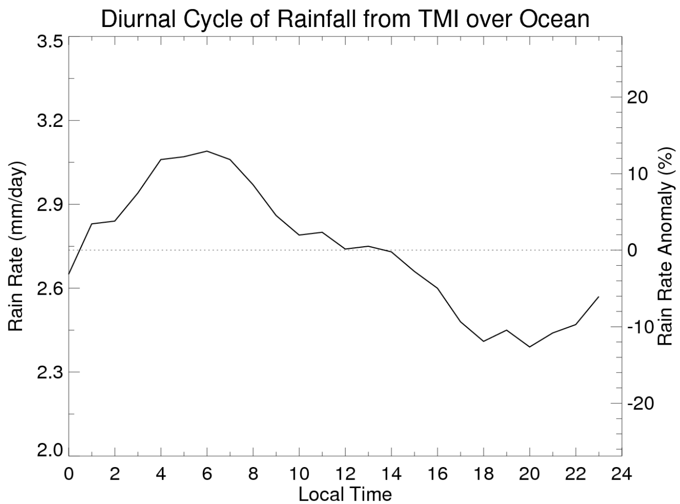
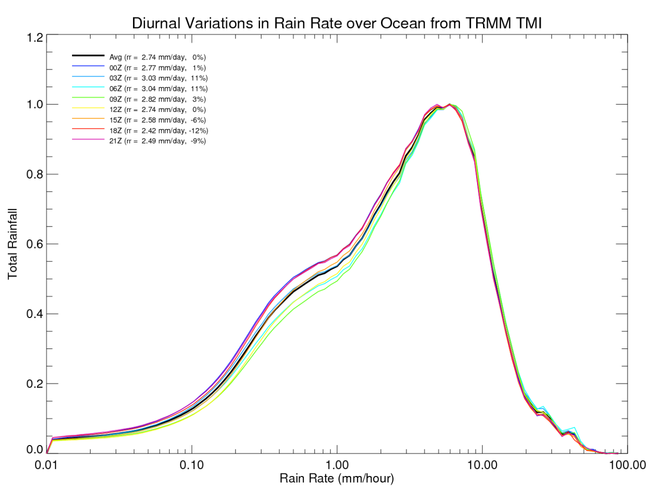


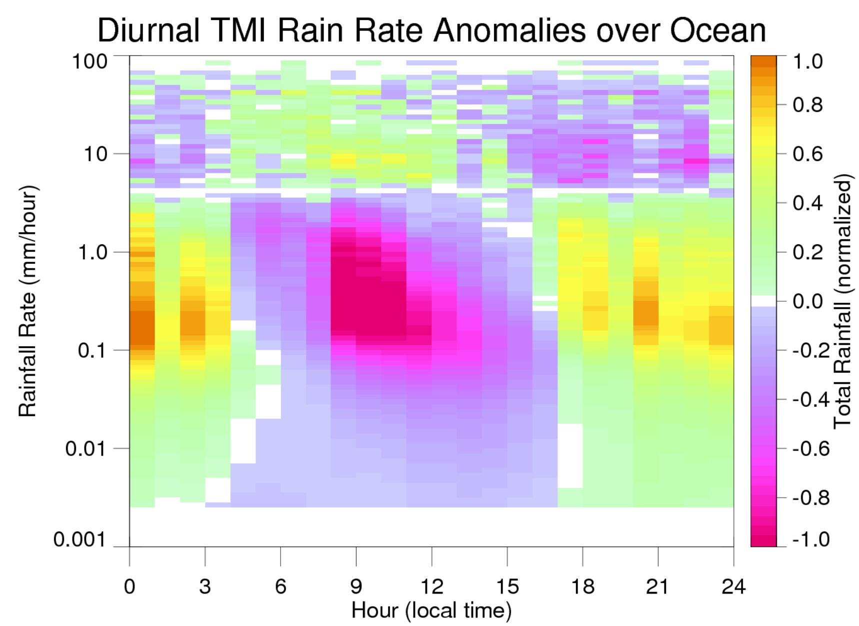
Image by Eric Nelkin (SSAI), 17 April 2013, NASA/Goddard Space Flight Center, Greenbelt, MD.

Diurnal Variability from TRMM TMI
Over Ocean

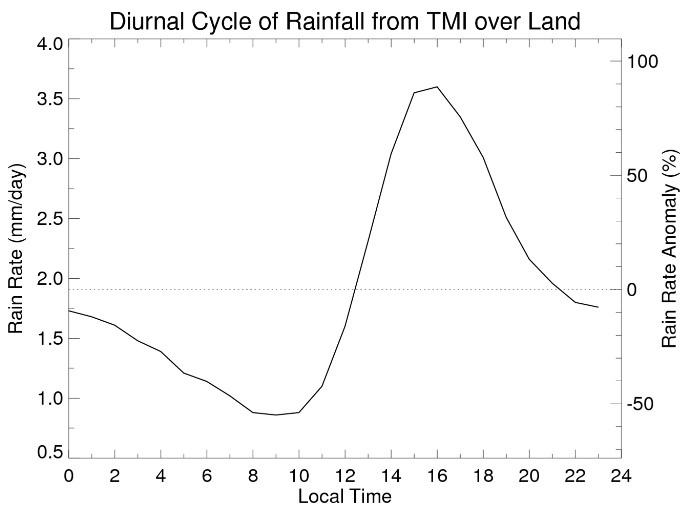


- Amplitude = ~10%
- Sinusoidal shape means sun-synchronous sampling should have minimal global bias (not true regionally)
- Largest change in rates rates between 0.1 and 1.0 mm/hour

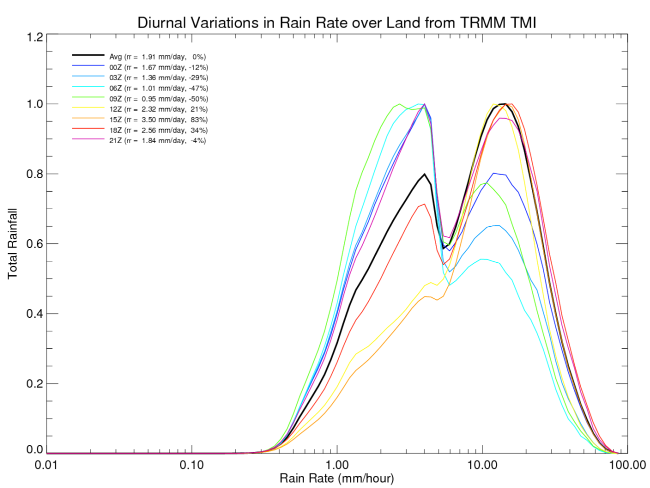


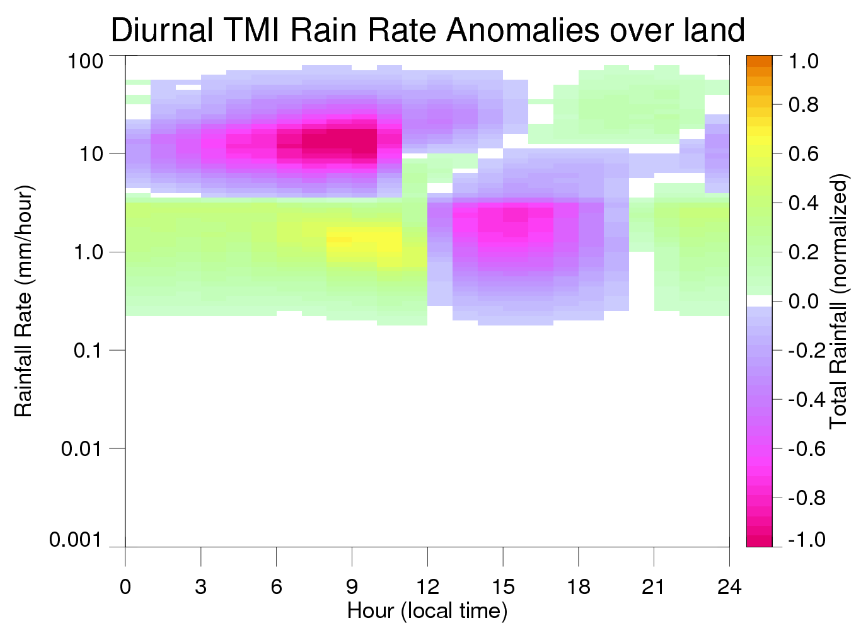


Diurnal Variability from TRMM TMI
Over Land

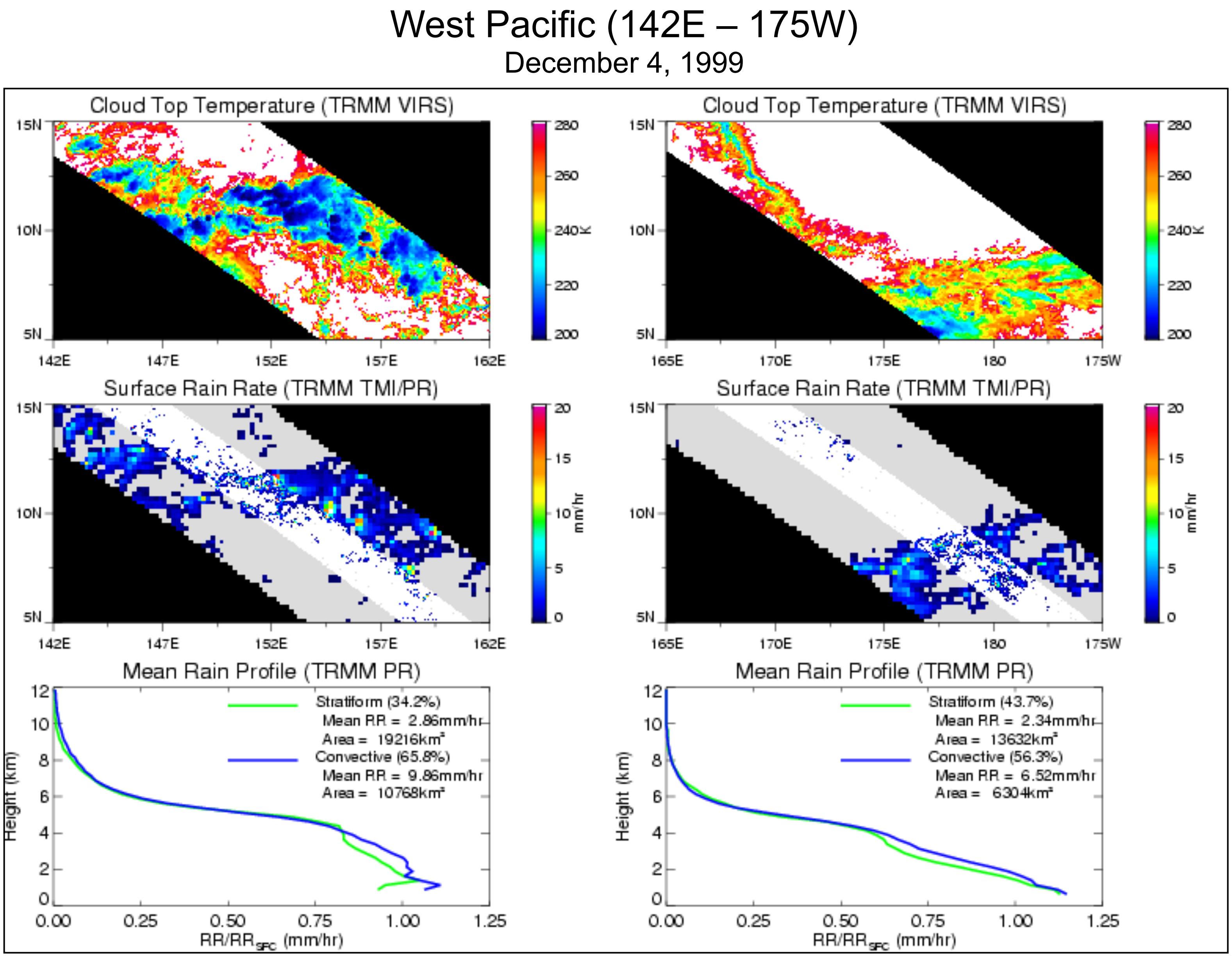


- Amplitude > 50%
- Shape is more susceptible to biases between sensors
- Largest change in rates rates between 0.1 and 1.0 mm/hour
- No algorithm sensitivity to warm rain or rain < ~0.5 mm/hour

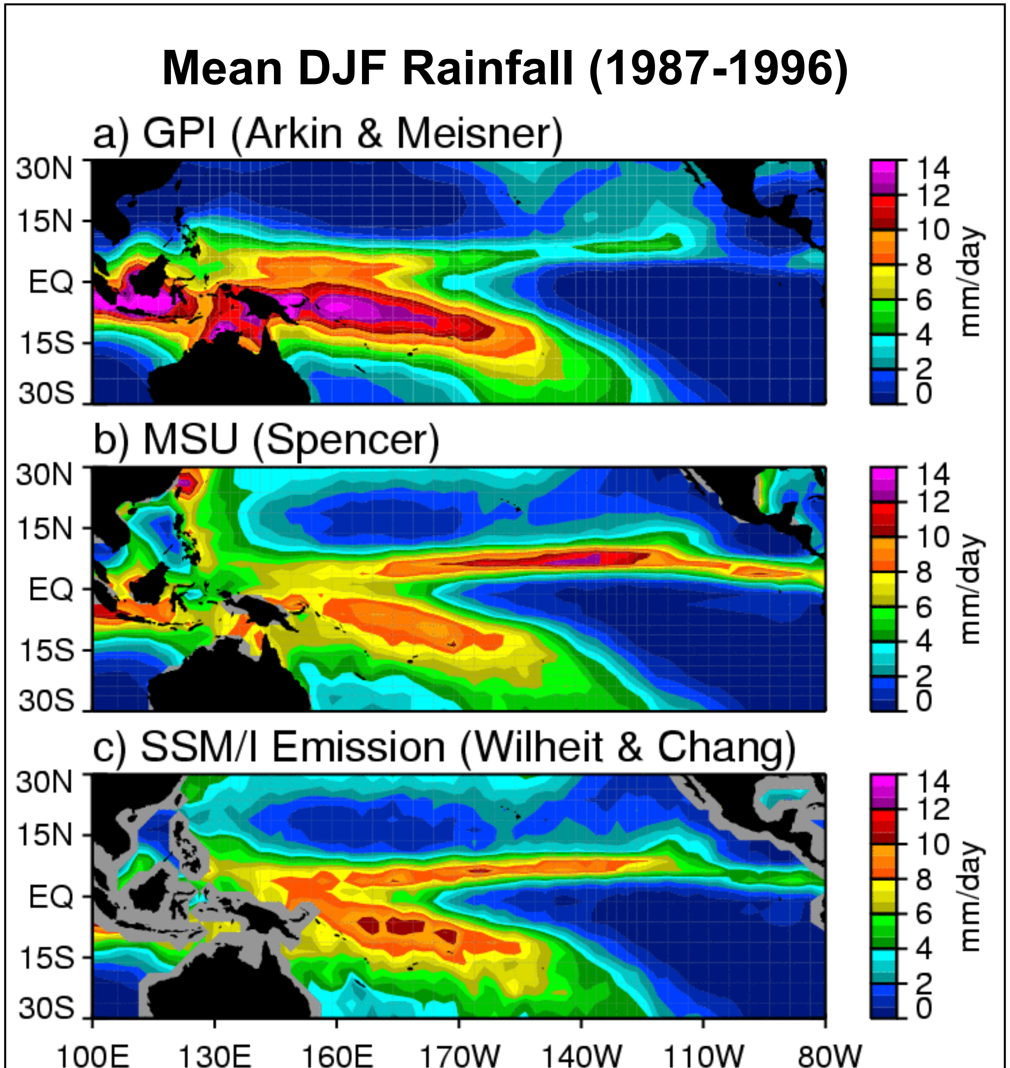




Dataset Differences → Information Content



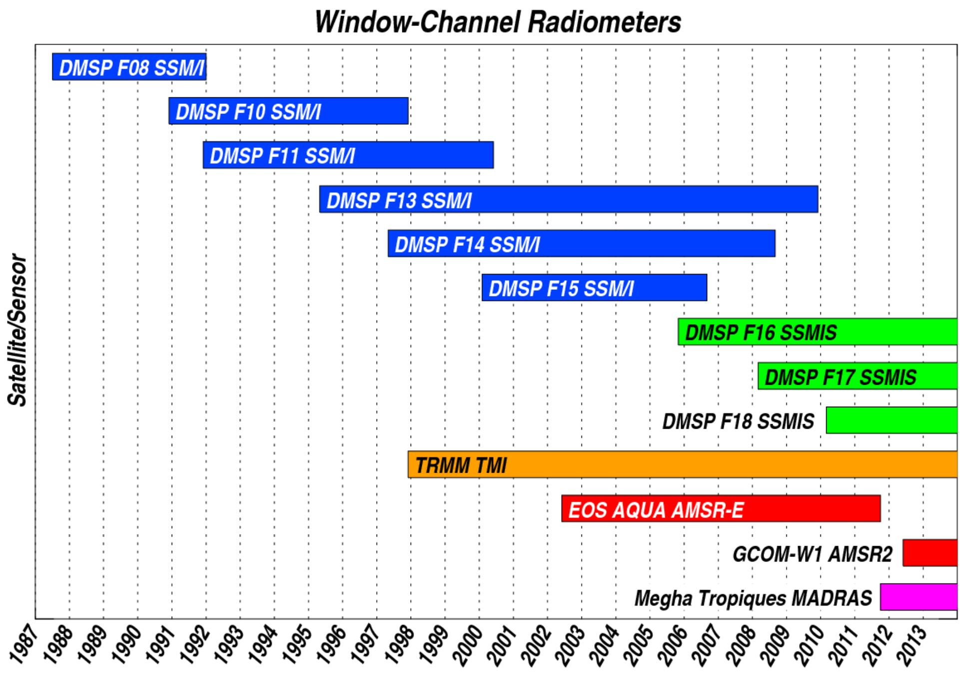
What does this Mean for Climate?



- For climate applications, random errors can effectively be reduced to very small levels by spatial and temporal averaging.
- Large-scale changes in cloud properties assumed to be constant by the retrieval algorithms can lead to systematic errors or biases. For example, GPI assumes the relationship of cloud-top temperature to rainfall is constant leading to a substantial underestimate of rainfall over the east Pacific.
- Changes in these assumed values over time, can also have significant impacts on the "observed" climate variability.

From Berg et al., 2002

Window-Channel Radiometer Precipitation Retrieval Algorithms



- Empirical/statistical
  - Long history including many current retrieval algorithms
  - Currently used over land in operational TRMM retrieval.
  - New algorithm being developed for GPM, which involves different approaches depending on ability to characterize land surface properties.
  - Works well for single sensor applications, but more problematic for constellation or time-dependent changes in sensor characteristics (e.g. loss of 85 GHz channels on F08)
    - Problems in application to different sensors (e.g. changing water vapor channel on imagers from 22.235->SSM/I(S) to 21.3->TMI to 23.8->AMSR or SSM/I 85.5 GHz to SSMIS 91.665 GHz).
    - Changes in view angle due to orbit decay etc. can also be an issue. Solution is generally to ignore or use look up table to adjust Tb to nominal value.

- Physically-based retrievals
  - Specification and radiative transfer modeling of horizontal and vertical distribution of microphysical parameters.
  - Important for consistency between sensors and for determination of uncertainties.
  - MIRS: NOAA's Microwave Integrated Retrieval System, which is an iterative, physically-based retrieval algorithm (1DVar)
  - GPROF 2010: A Bayesian retrieval which uses an apriori database developed from combined TRMM TMI and PR observations with CRM sims to provide microphysical information. This allows application to other sensors to produce physically consistent retrievals as well as changes such as EIA due to orbit decay or TRMM orbit boost.

TRMM 2A12 V7 = GPROF 2010. The 2A12 algorithm is the operational TMI version of the GPROF 2010 algorithm, which is the non-sensor specific designation. GPROF 2010 is a physically-based Bayesian retrieval over ocean, but an empirically-based scattering algorithm over land.

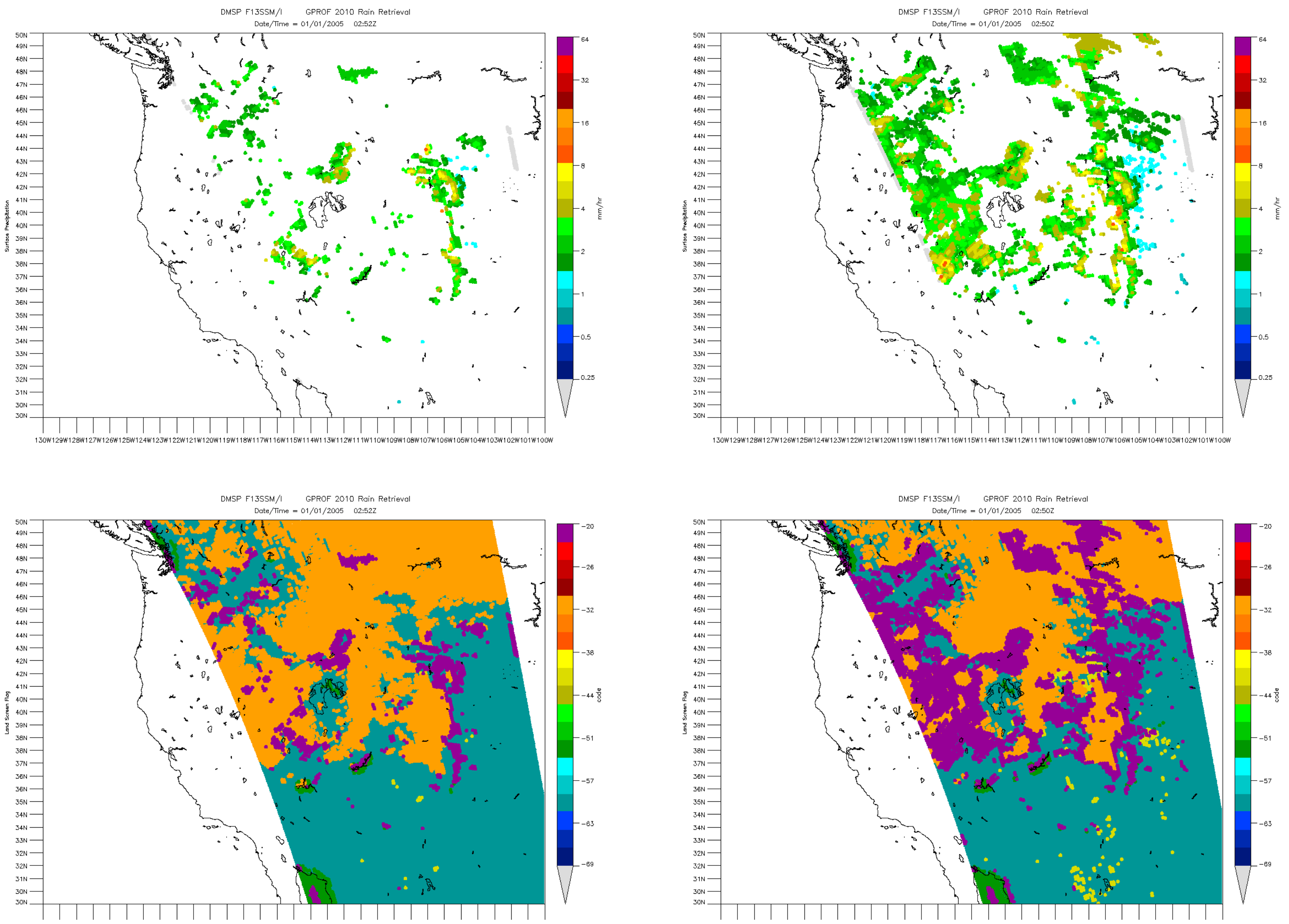
GPROF 2010 Rainfall Screen over Land

Impact of 22 GHz TB Difference

RSS FCDR | CSU FCDR

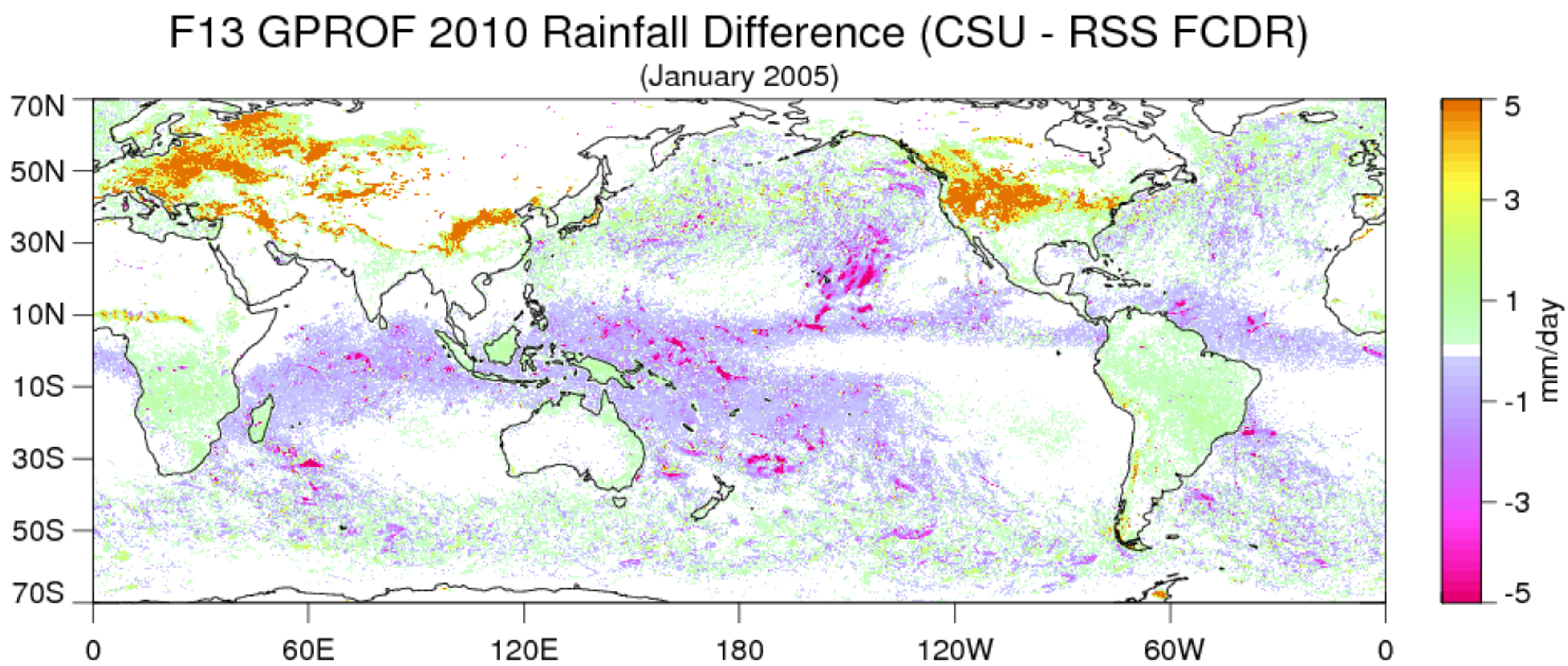
Rainfall

Rain Screen



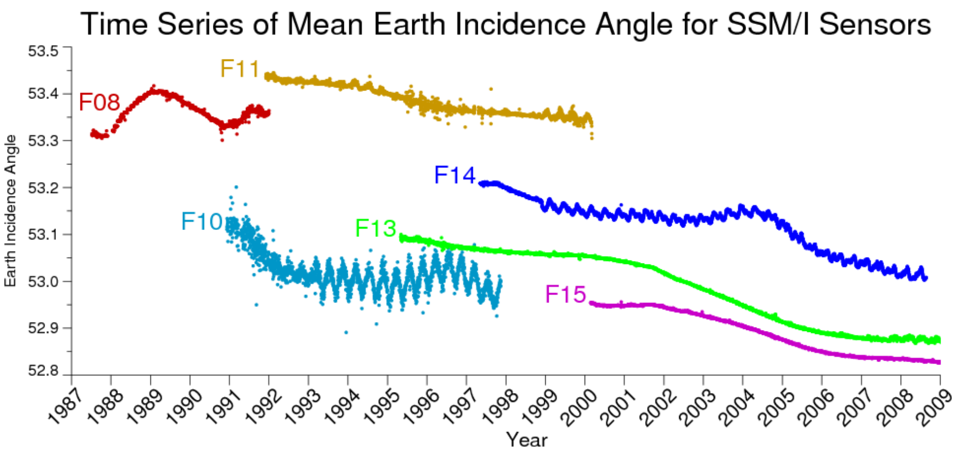
Impact of Calibration on GPROF 2010

CSU vs. RSS FCDR Brightness Temperatures

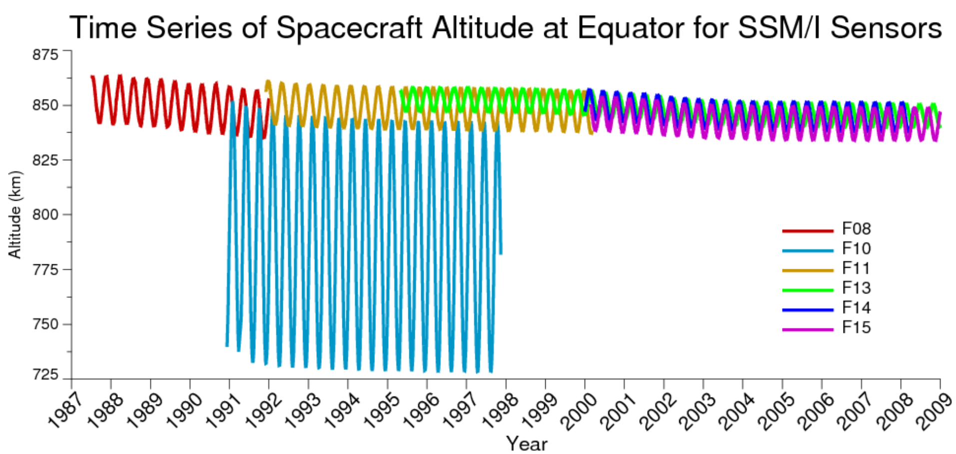


Variation in Mean EIA over Time

CSU FCDR



CSU FCDR



- Differences in Mean EIA are small for some sensors (i.e. F11, F13, F15), but as much as 0.2 degrees or more for F10 and F14.
- EIA trend due primarily to decrease in spacecraft altitude over time. Due to the larger eccentricity of the F10 orbit its variability over time is significantly larger.
- These small variations in EIA can have a significant impact on retrievals, especially surface wind speed, and thus evaporation.

Physical Retrievals

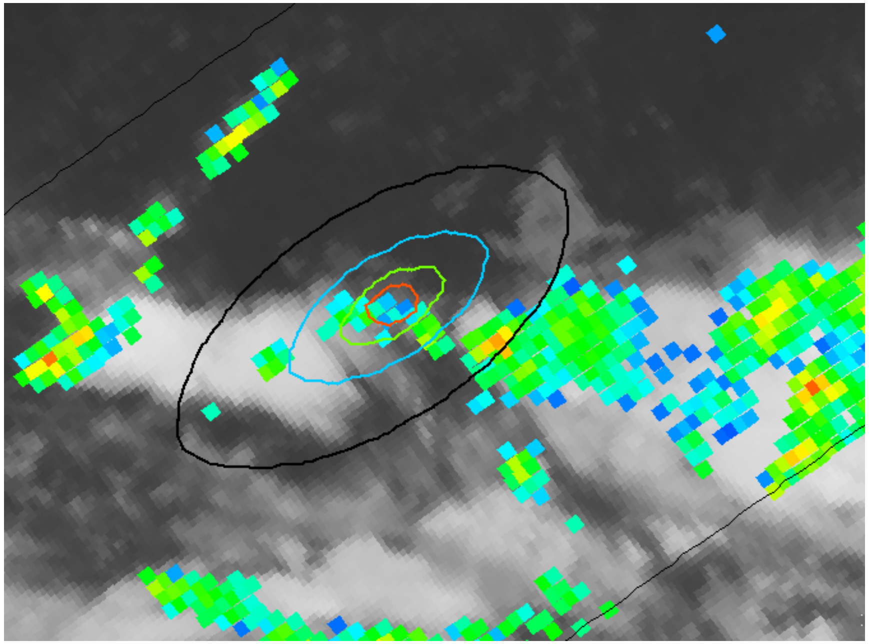
Modeling microwave Tbs requires knowledge of:

<u>Non-precip parameters:</u>

- Surface emission (SST,wind)
- Air temperature
- Water vapor
- Cloud water

<u>Precip parameters:</u>

- Precipitation ice
- Melting layer
- Rain water



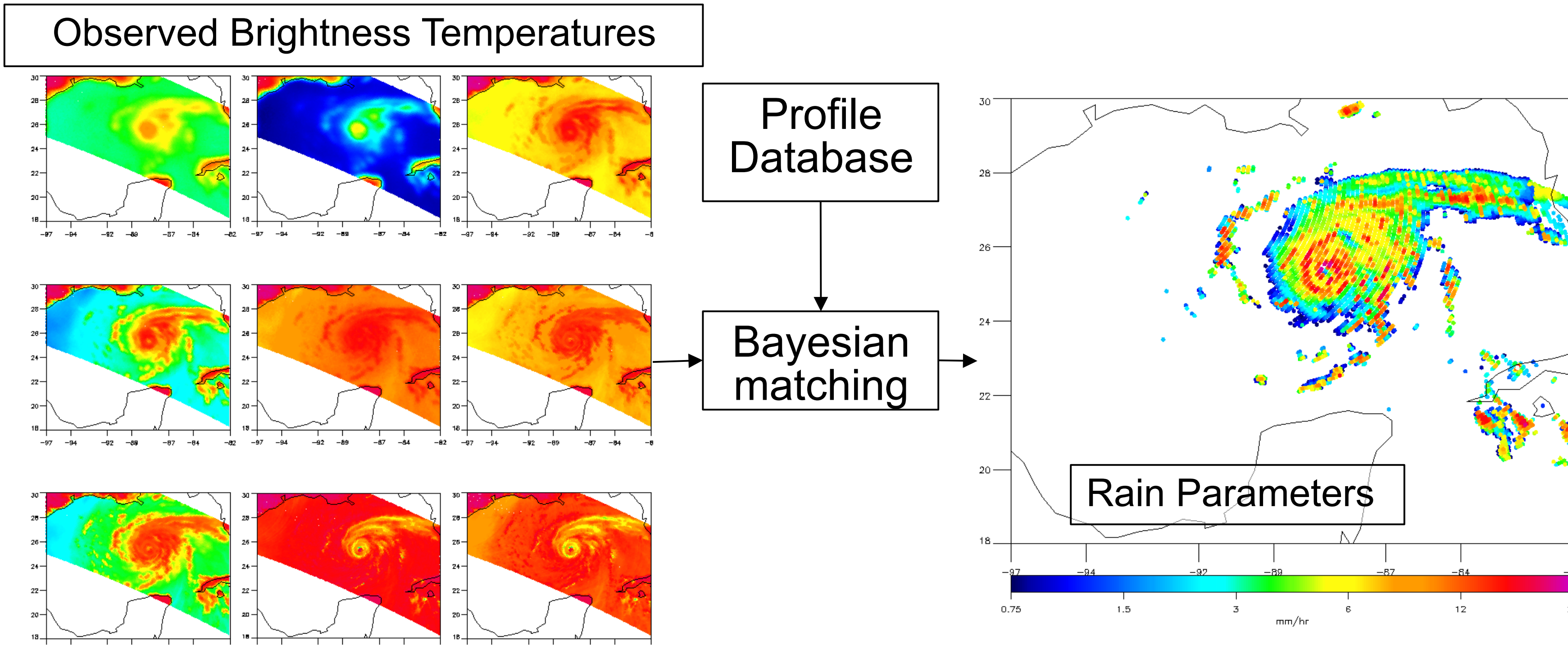
Courtesy Joe Munchak

Fundamentals of the Bayesian Retrieval

GPROF 2010 Implementation

- The radiometer retrieval is fundamentally underconstrained given only 9 brightness temperatures for TMI (7 for SSM/I), which are not all independent. This means that pixels with similar Tb can have different structure and other characteristics.
- To deal with this GPROF uses an apriori database containing rain rates and profile information along with Tb. This database was constructed using matched TMI and PR information along with hydrometer profiles from CRM simulations.
- The Bayesian approach utilized by GPROF averages a number of profiles from the database with similar Tb. As a result, profiles from very different rain systems can get averaged together.
- The apriori database is stratified by SST and TPW to distinguish between raining profiles with similar Tb, but from different regimes.
- The **V7 database** modifies the hydrometeor profile in a bulk statistical sense to better match both the PR reflectivity profile and TMI Tb. This results in changes in the surface rain rates from the original 2A25 estimates in the final v7 database. This involves both DSD changes as well as the additional of light rain to high Tb emission (i.e. high liquid water) scenes with RR_{PR} = 0.

TMI Retrieval Algorithm (2A12/GPROF 2010)
(over ocean)



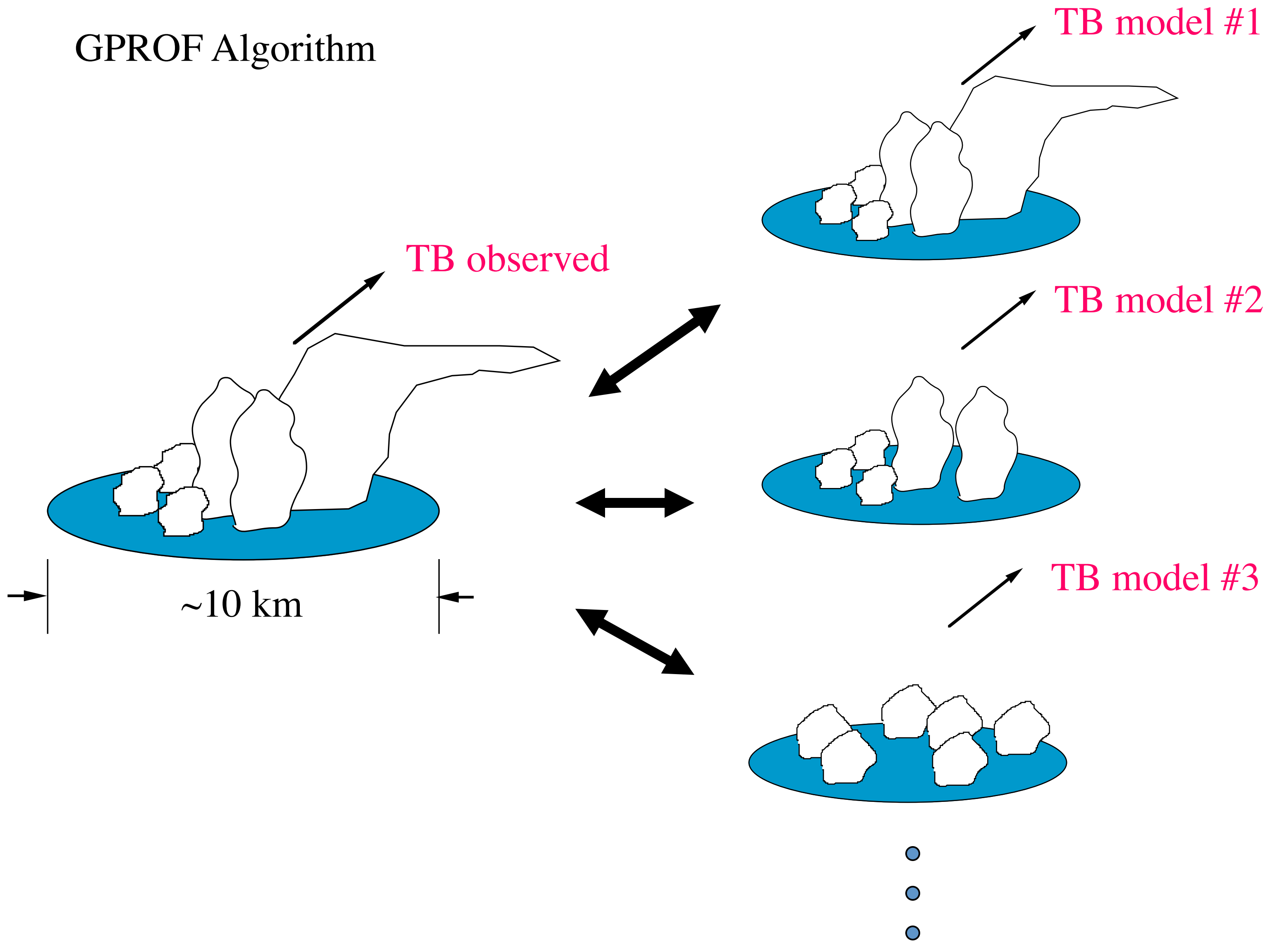
Algorithm assumptions:

- Vertical profile
- Surface emission
- Rain water/cloud water partitioning
- Rain DSD, ice properties

Instrument Limitations:

- Mismatched, low resolution fields-of-view (FOVs)

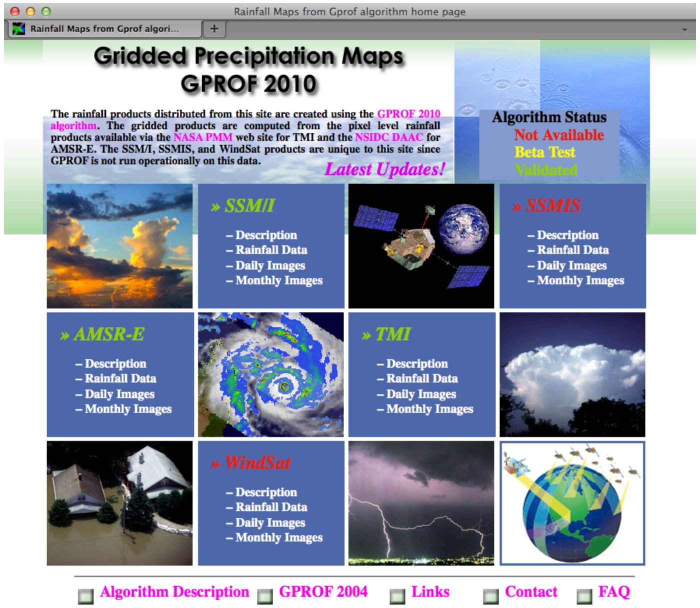
Courtesy Joe Munchak

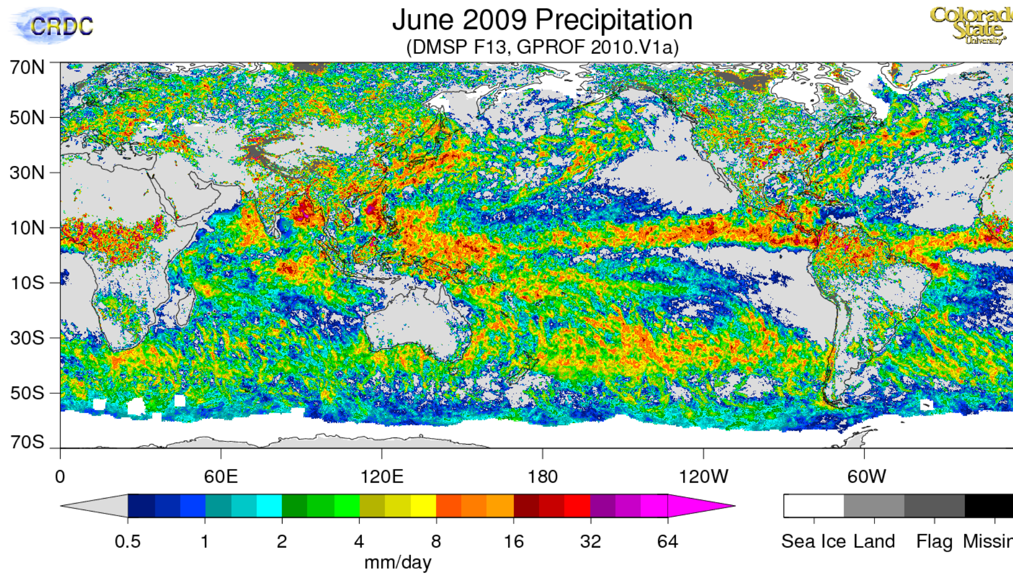


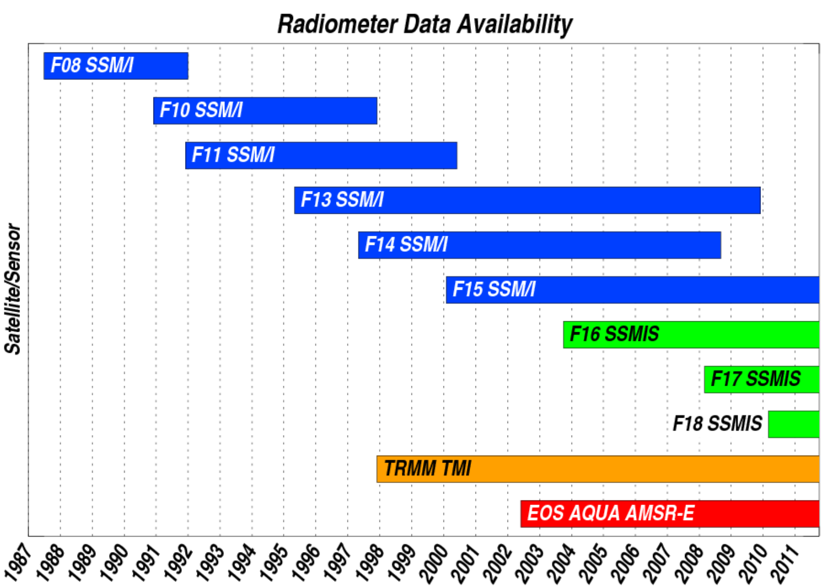
GPROF Algorithm
TB observed
~10 km
TB model #1
TB model #2
TB model #3

GPROF 2010 Rainfall Products

http://rain.atmos.colostate.edu





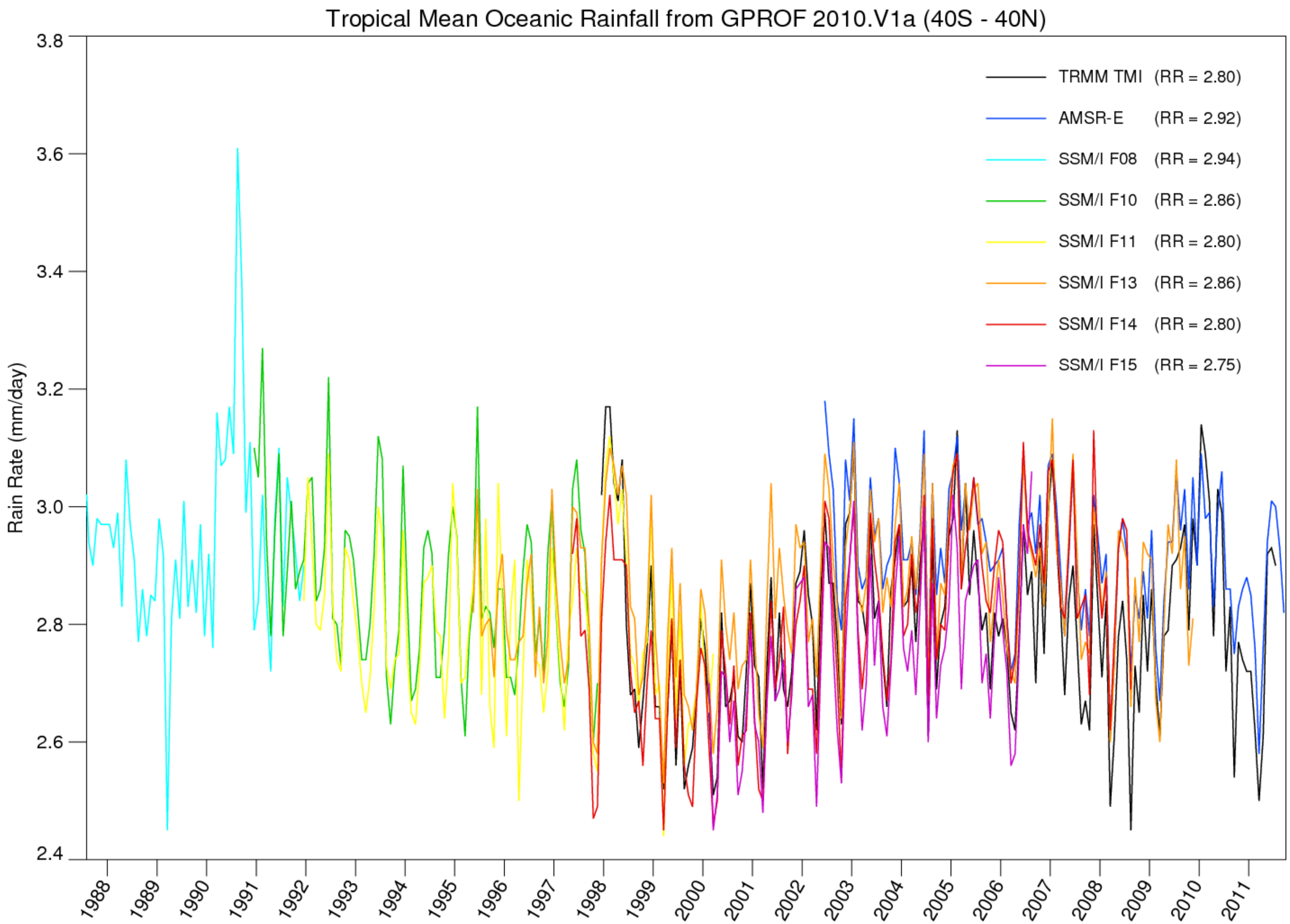


Level 3 Gridded Rainfall Products

- F08, F10, F11, F13, F14, F15, TMI, and AMSR-E
- F16, F17, and F18 to be added in the future
- Gridded 0.25x0.25 degree Daily and Monthly
- Download options include binary data files, static Images, and dynamic plotting tool
- Also Includes SST, TPW, ocean wind speed, cloud water path, rain water path, ice water path, number of pixels, surface and quality flags

GPROF 2010 Rainfall Time Series

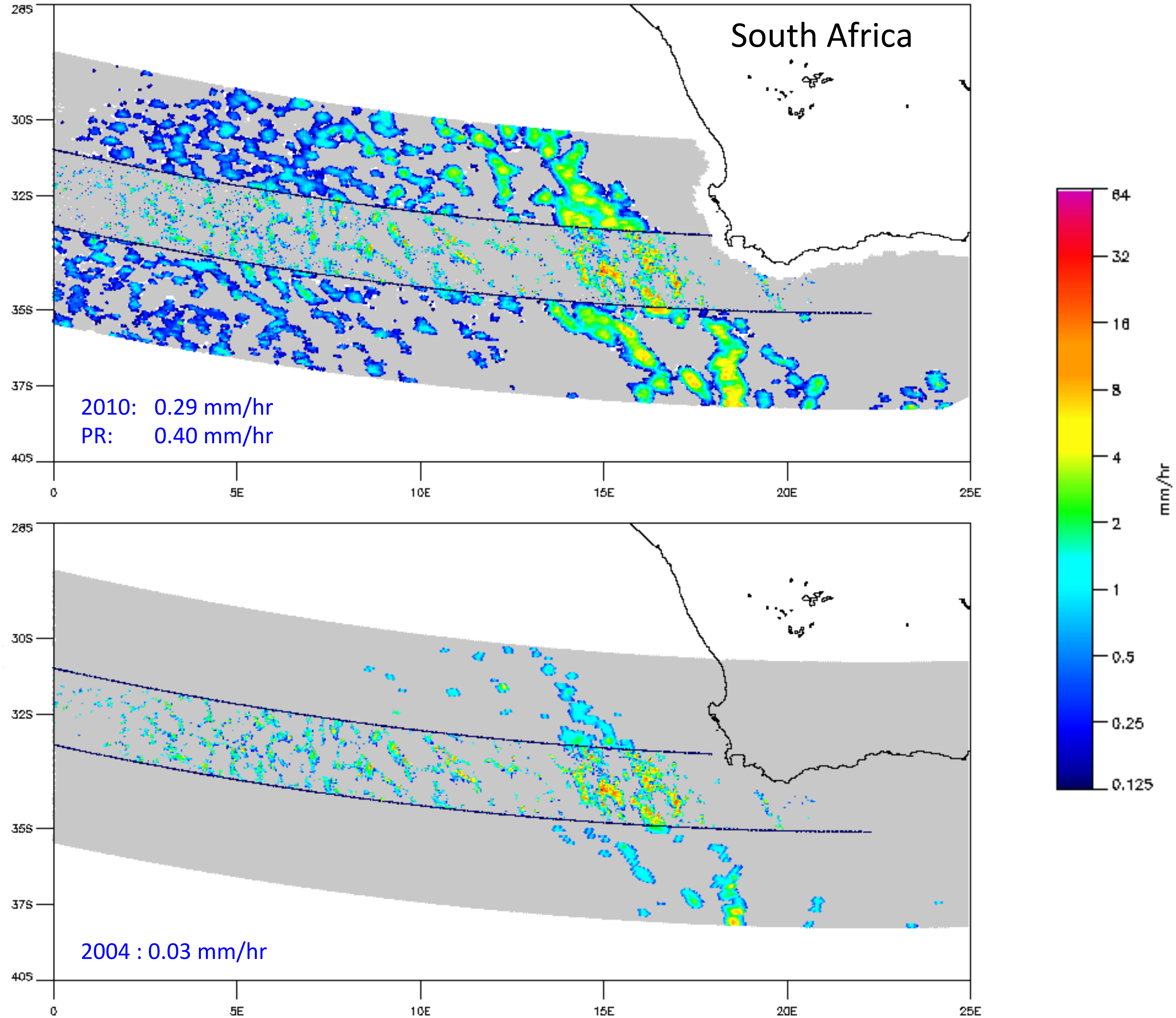
SSM/I, AMSR-E, and TMI



8 September 1999

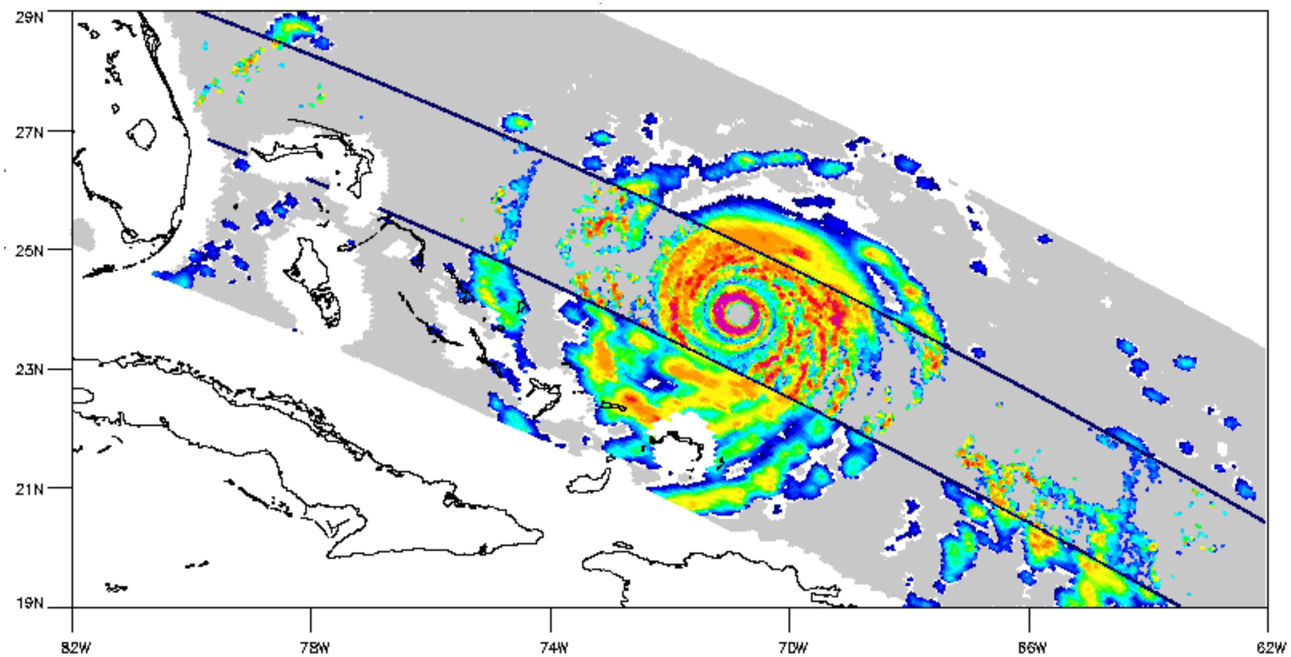
GPROF 2010
TRMM 2A12 V7

GPROF 2004
TRMM 2A12 V6

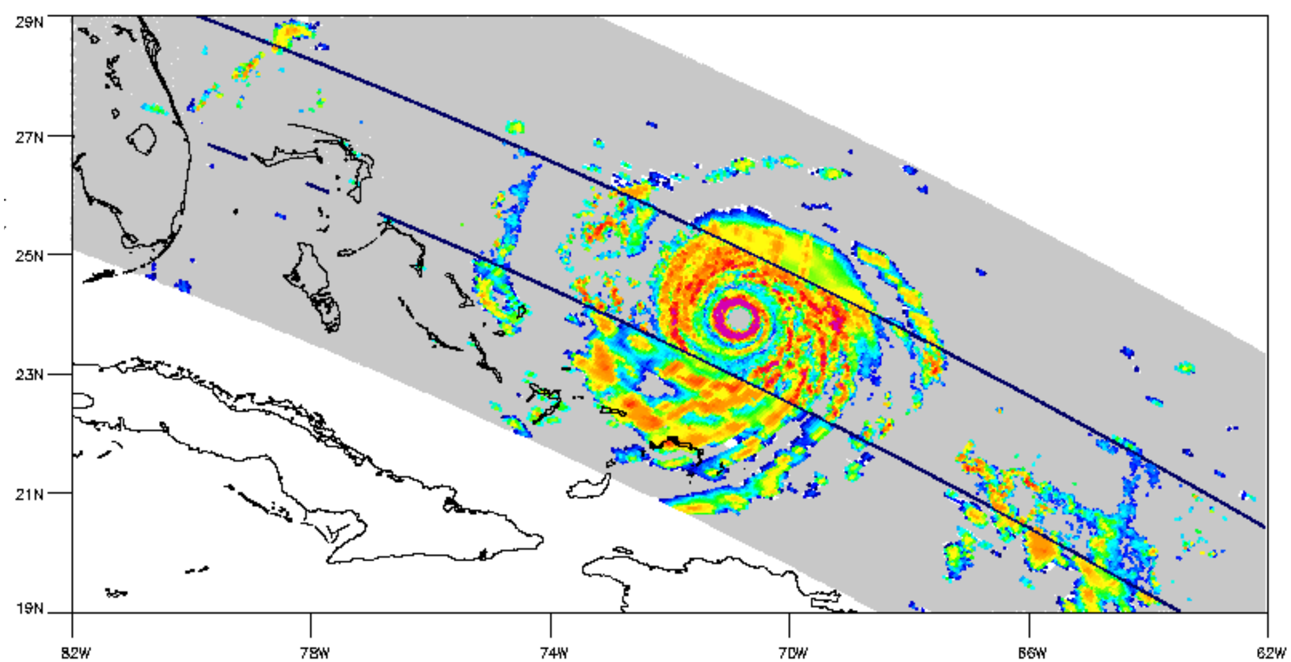


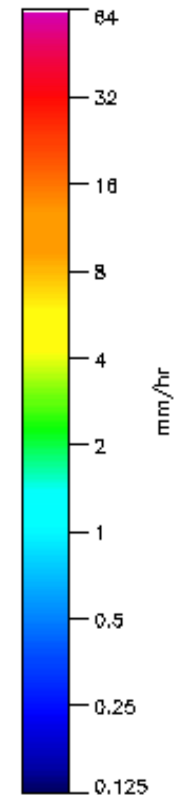
Hurricane Floyd
13 September 1999

GPROF 2010

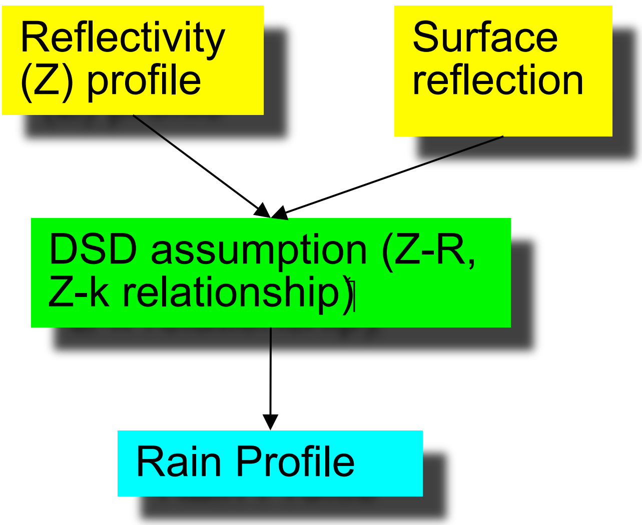


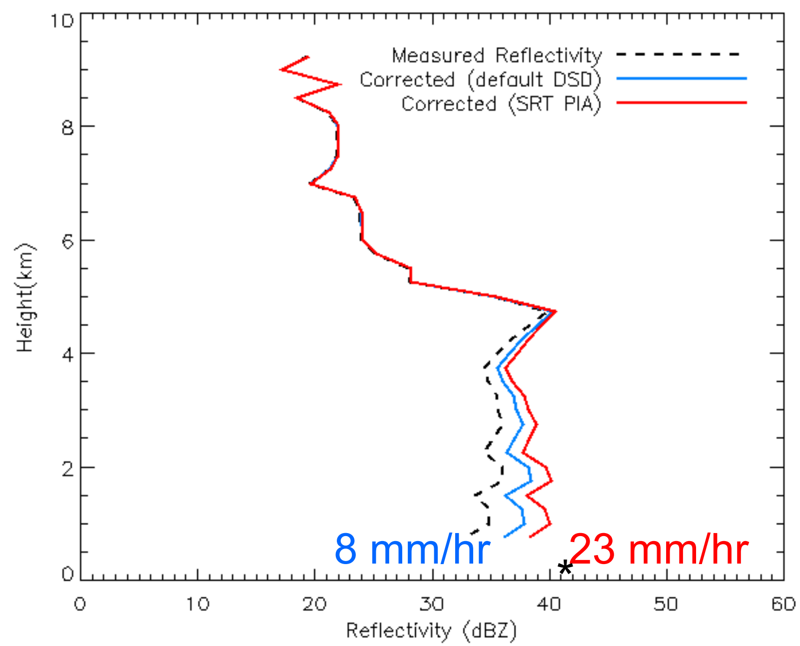
GPROF 2004





PR Retrieval Algorithm (2A25)





Instrument Limitations:

- Single Frequency
- Minimum detectable echo (~17 dbZ)
- Ground Clutter
- Noisiness of surface reference technique (SRT)

Algorithm Assumptions:

- Raindrop size distribution (DSD)
- Vertical model assumption

Courtesy Joe Munchak

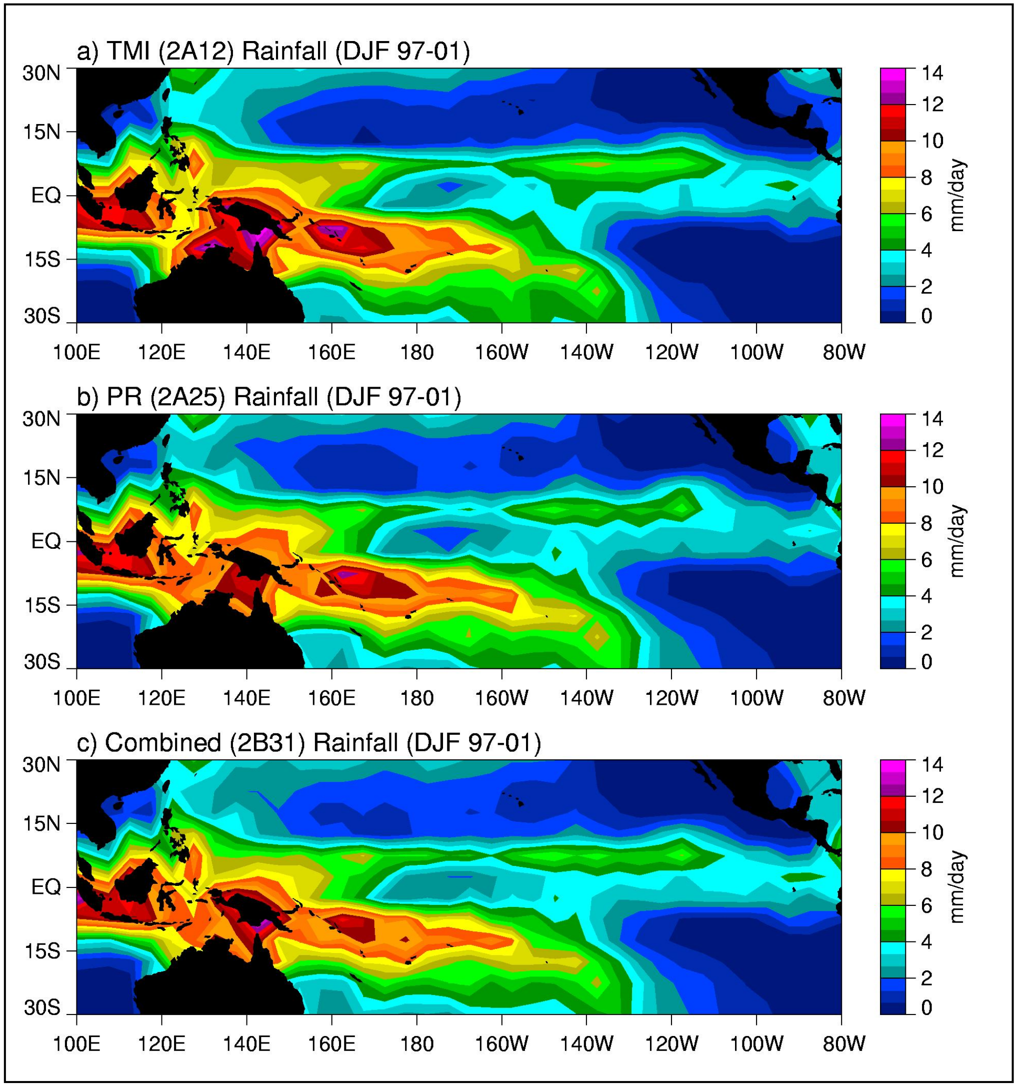
TRMM Precipitation Retrieval Evolution

TRMM provided simultaneous observations from two high-quality rainfall sensors. They are based on very different physics and thus provide independent estimates (prior to 2A12 V7).

Analysis of differences between the very different physics and techniques used to estimate precipitation from the active radar (PR) and passive microwave (TMI) has led to a number of significant discoveries and algorithm improvements.

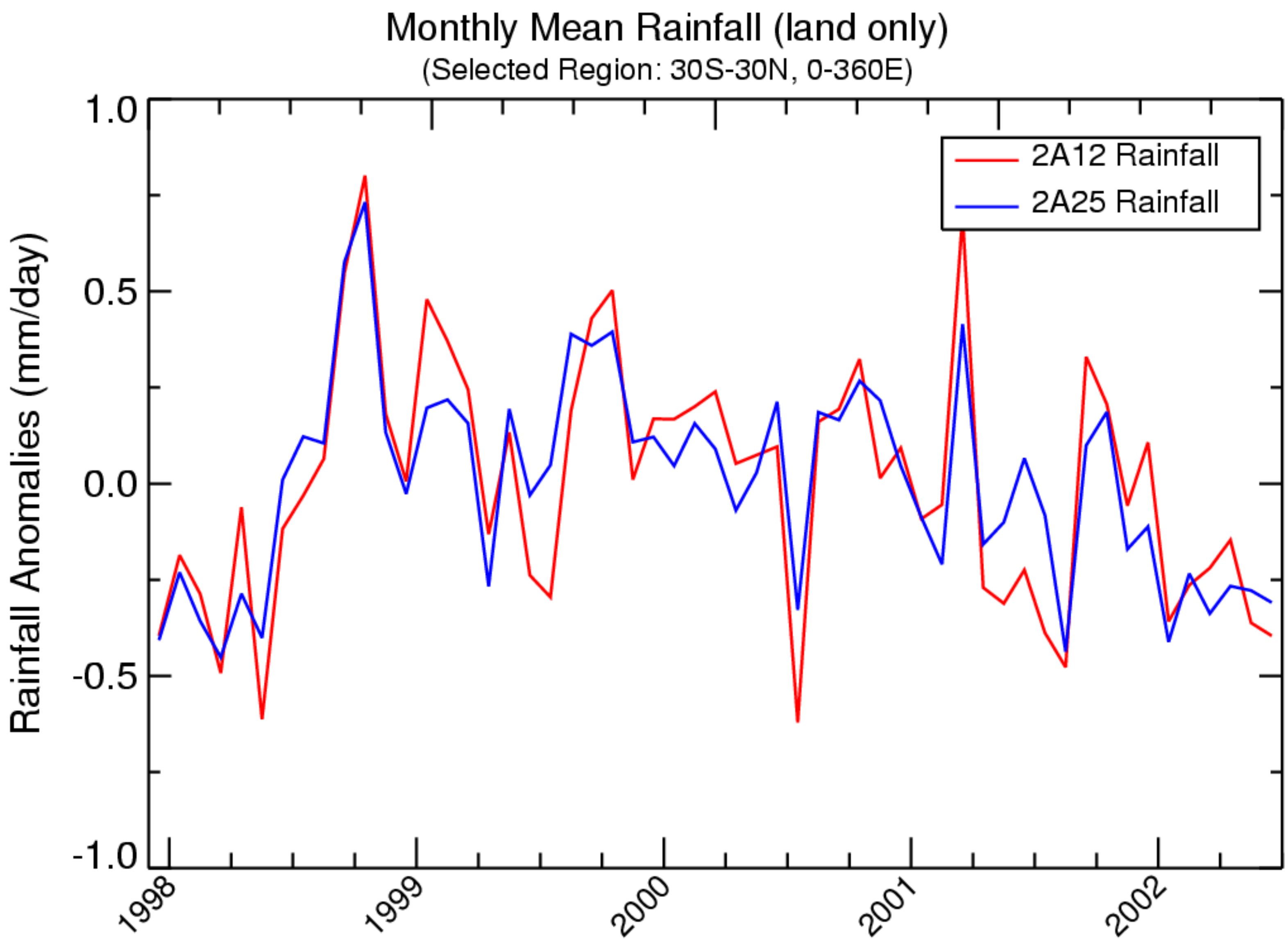
GPM will expand on this added a second radar and high frequency microwave channels.

TRMM Dataset Differences

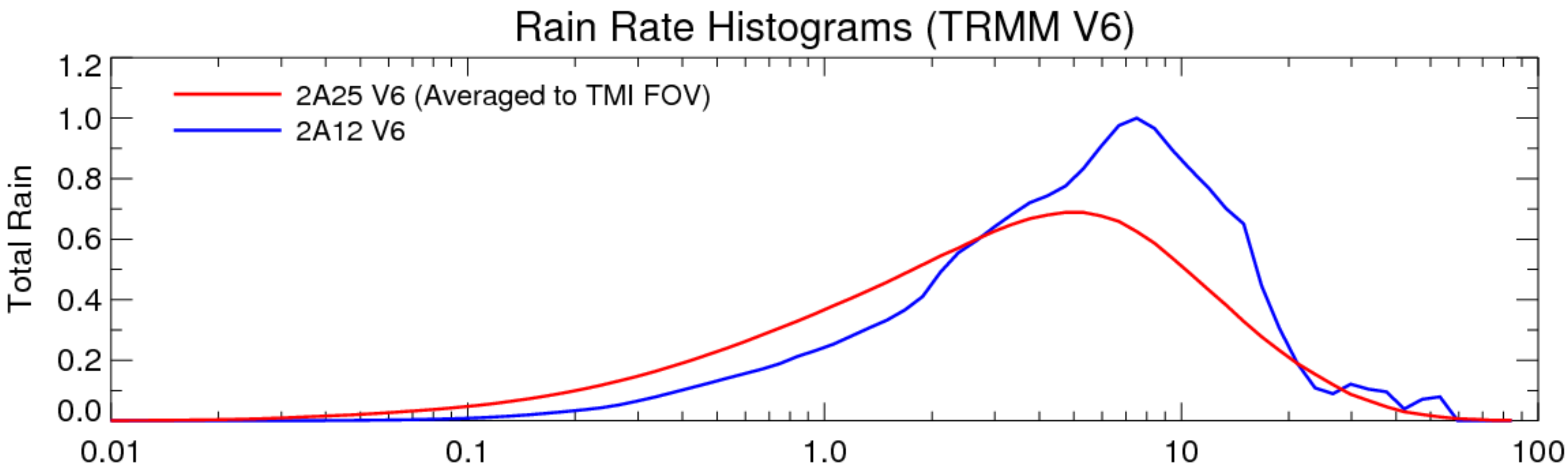


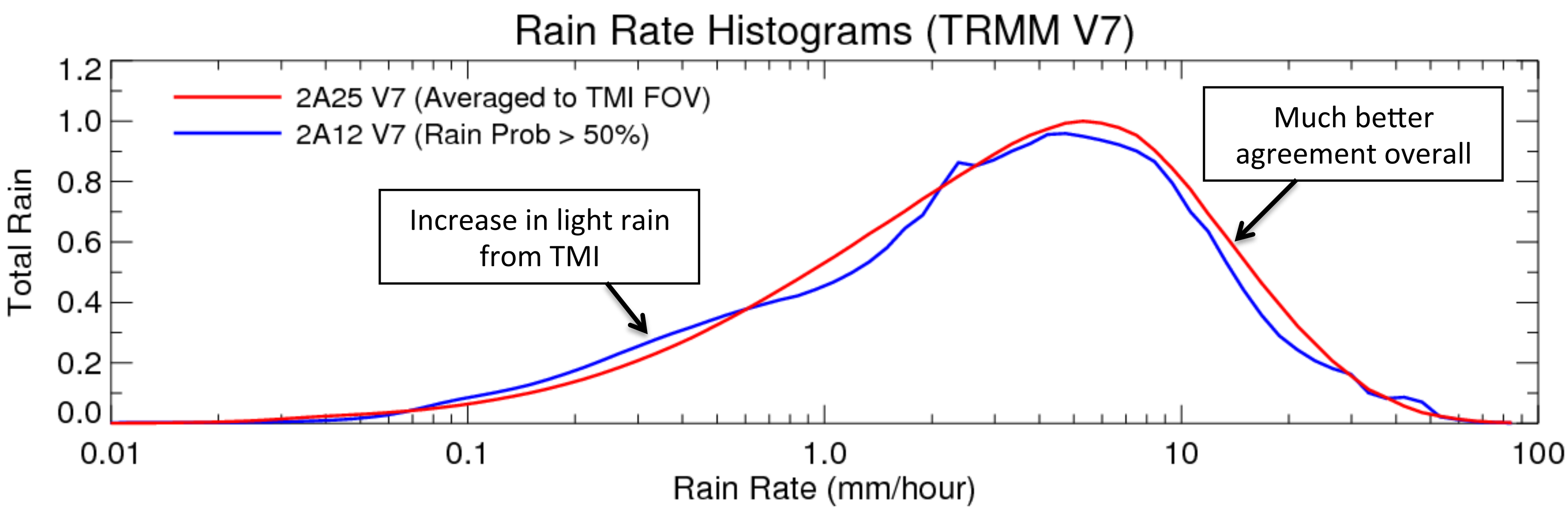
Tropical Rainfall Anomalies

(TRMM Land Retrievals)



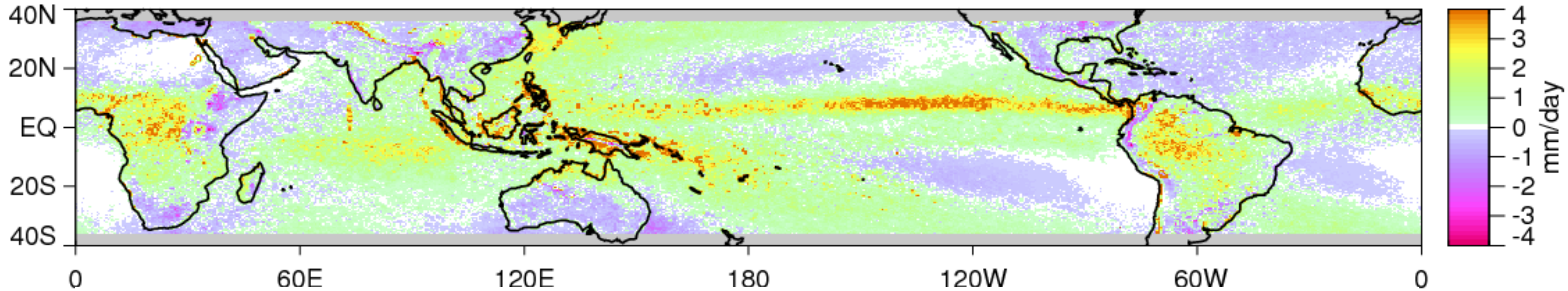
Rain Rate Distributions



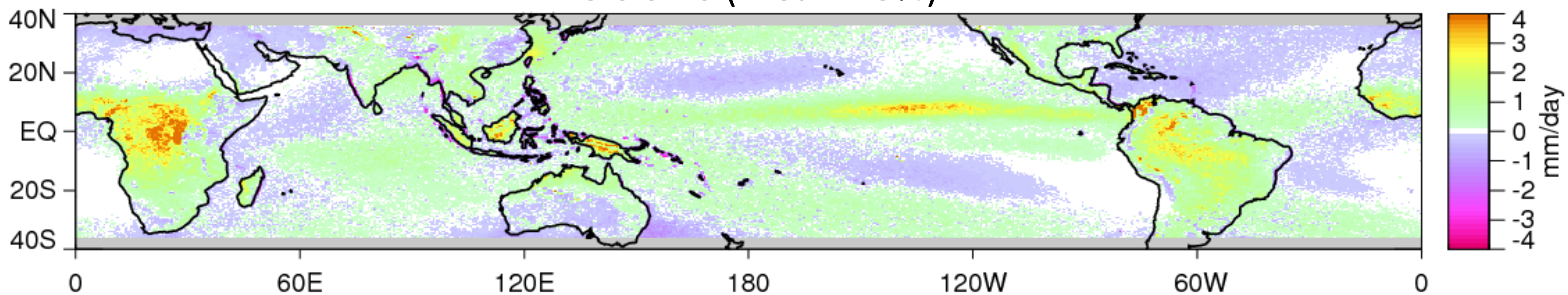


Regional TMI – PR Differences

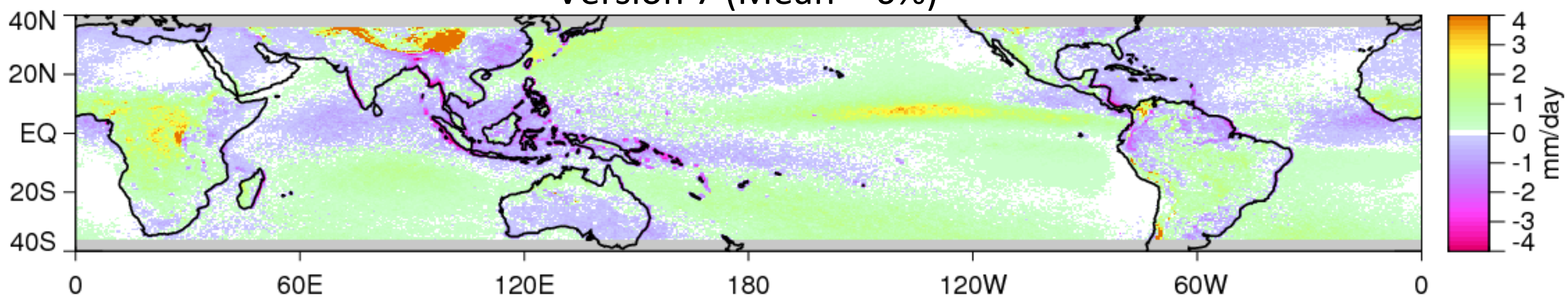
Version 5 (Mean = 23%)



Version 6 (Mean = 9%)

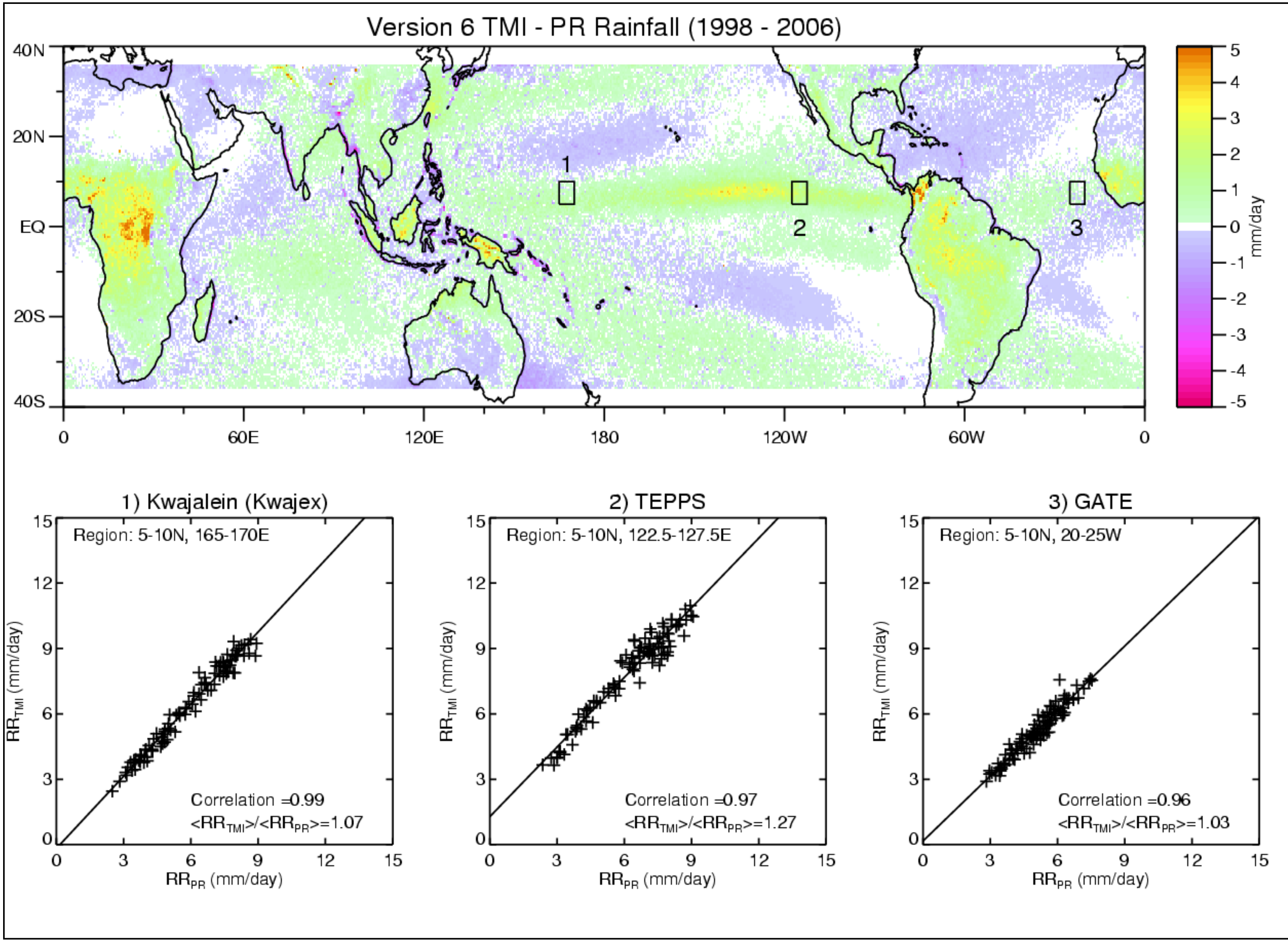


Version 7 (Mean = 6%)

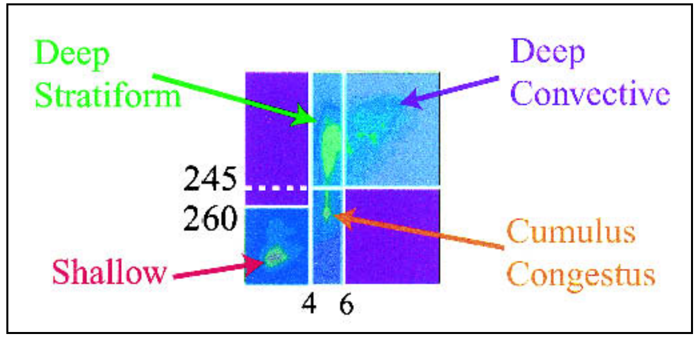


TRMM V6 PR/TMI Rainfall Differences

Regional Differences

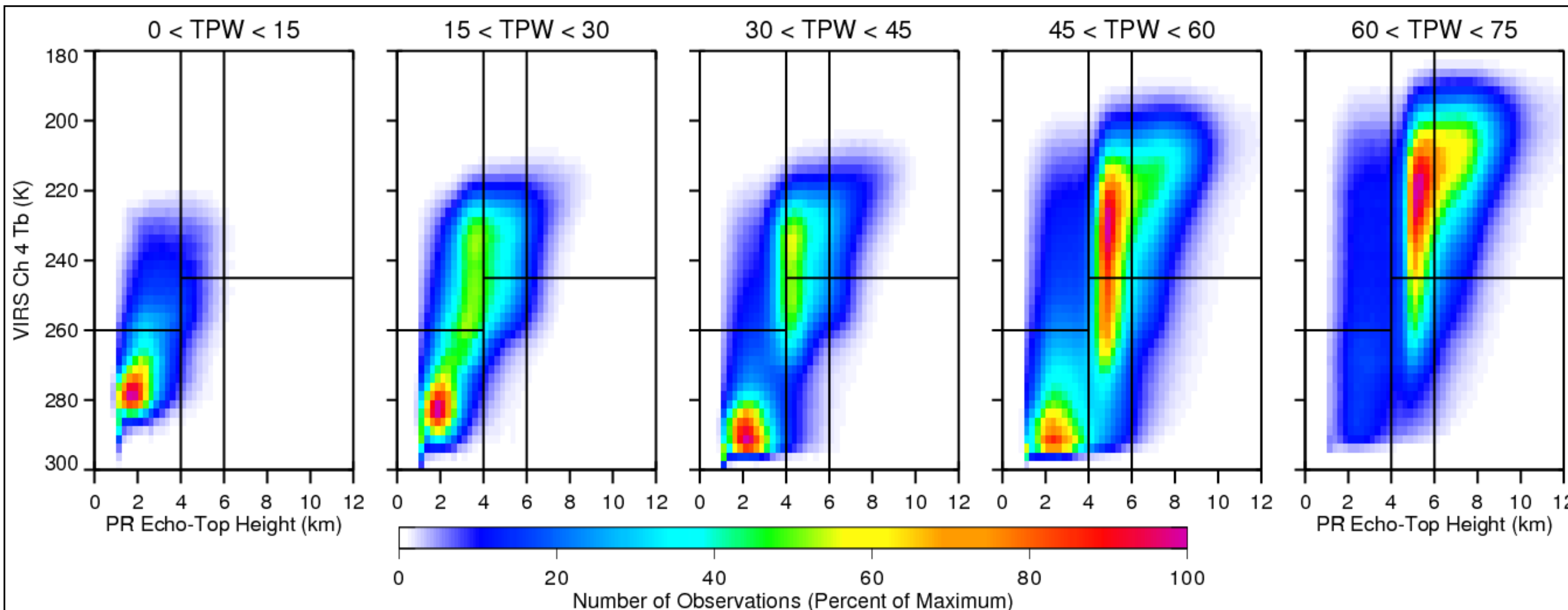


2D Histograms of PR Echo-Top Height and VIRS IR Brightness Temperature



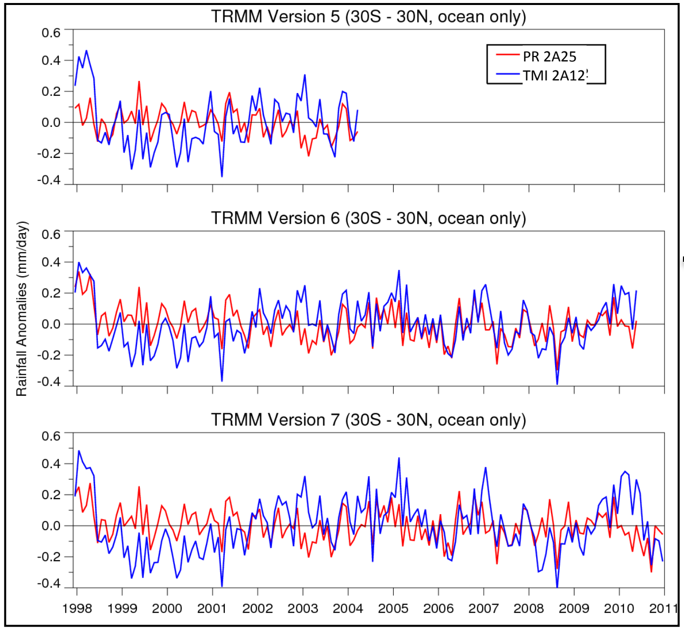
From Masunaga et al. 2005

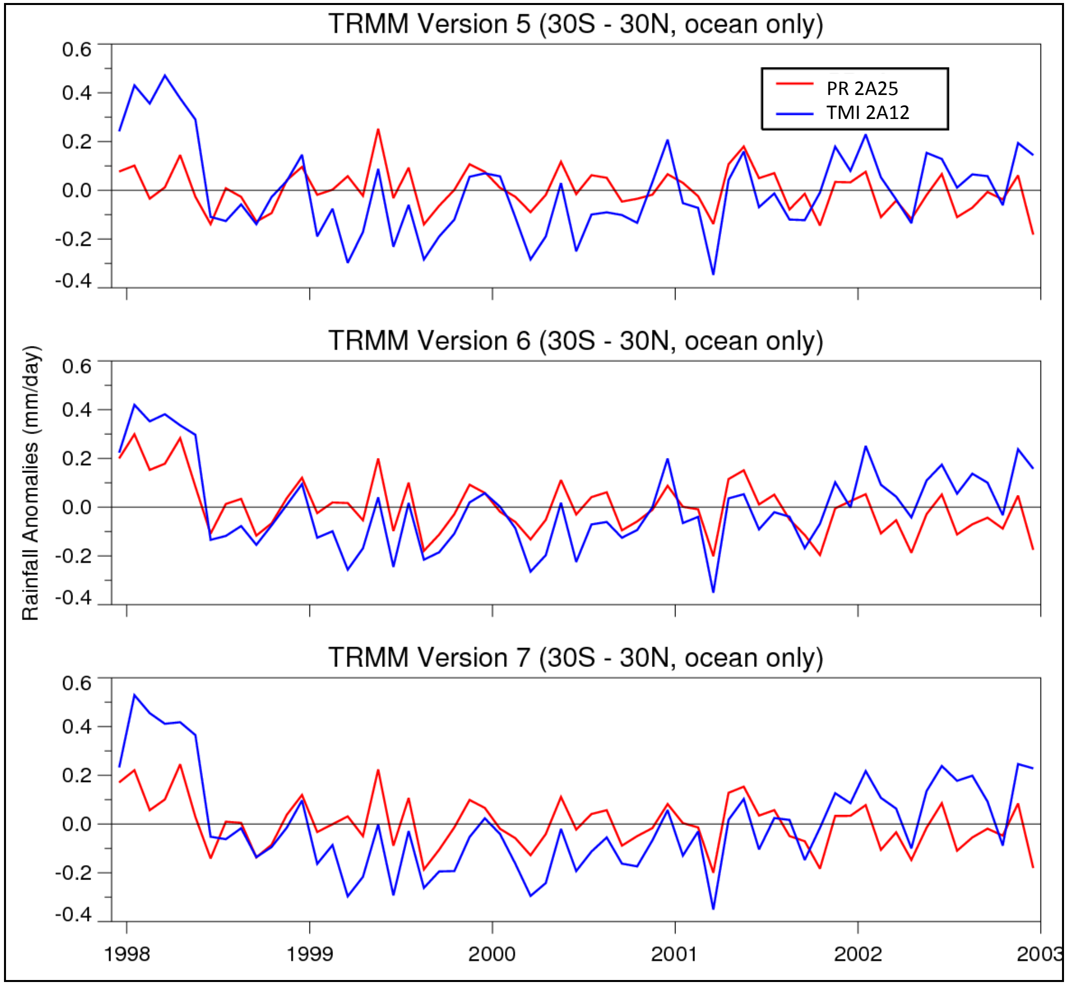
2D Histograms as a Function of Total Precipitable Water



Time Series of TRMM Precipitation Anomalies

Tropical Mean Oceans (30S to 30N)





- V5 PR time series shows no increase in rain associated with 97/98 ENSO
- V6 PR shows ENSO increase
- V7 PR ENSO increase is less than V6
- Small change in interannual variability of TMI rainfall between versions
- PR rainfall anomalies relatively flat over time while TMI anomalies show significant interannual variability

Sources of Uncertainty
Algorithm Assumptions

IR Retrievals

- Relationship of cloud-top temperature to surface precipitation rate

Radiometer (ocean)

- Freezing level
- Shape of precipitation profile
- Beam Filling -> Inhomogeneity in FOV

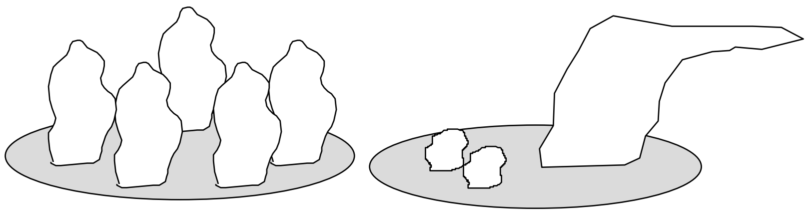
Radiometer (land)

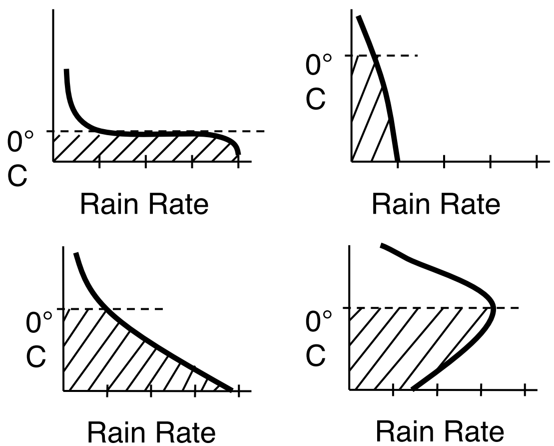
- Relationship of ice aloft to surface precipitation
- Emission from warm rain obscured by surface variability

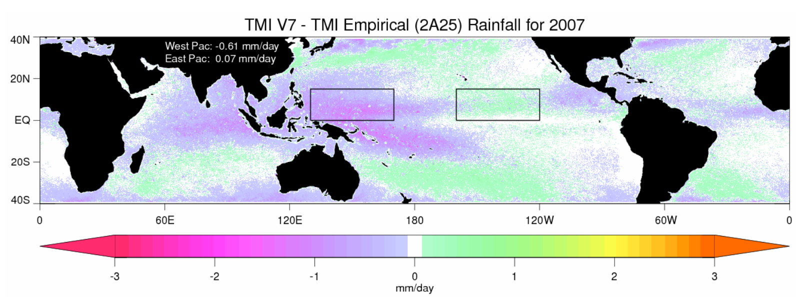
Radar

- Drop size distribution
- Beam Filling -> Inhomogeneity in FOV
- Attenuation Correction

Potential Sources of Regime Biases







- Inhomogeneity in FOV
  - FOV sizes: ~15km for TMI and ~5km for PR
  - Were the changes to the NUBF correction in 2A25 from V5 to V6 to V7 a significant part of the change in the ENSO response?
  - This could be an issue for TMI and other radiometers due to large footprint size, although apriori database uses 5km PR data.
  - Analysis of PR variability within TMI FOV indicates significant differences between East and West Pacific. Impact is less certain.
- Vertical profile and Freezing Height
  - Minor issue for PR/DPR due to surface clutter and extrapolation to surface
  - Potentially a significant issue for TMI since Tb respond to changes in the column integrated water/ice, particularly at high latitudes
  - It is likely that changes in the vertical profile are related to the inhomogeneity.
- Microphysics (i.e. DSD)
  - Differences between V7 and Empirical results suggest this is a factor, but may only account for a portion of the differences.
  - GPM DPR should provide information to identify and hopefully largely resolve this issue
- – Sensitivity
  - Light Rain missed by PR and potential changes in cloud water/rain water partitioning by TMI. Increased sensitivity of GPM KaPR and high latitude orbit will help significantly to quantify this.
  - Snow. This will remain a big challenge even for GPM.

Radar Rainfall for 40 dBZ
(Battan, 1973)

Location	Rainfall rate [mm/hr]
Canada	48.6
Hawaii	112.6
Midwest	50.2
Australia	10.2
Washington, DC	54.0
Massachusetts	254.0
Moscow	40.0
Poon, India	43.0
France	24.2
Franklin, NC	76.7

Motivation for developing a new combined algorithm

Key question: **Can a combined algorithm improve upon radar- or radiometer-only product biases in multiple locations?**

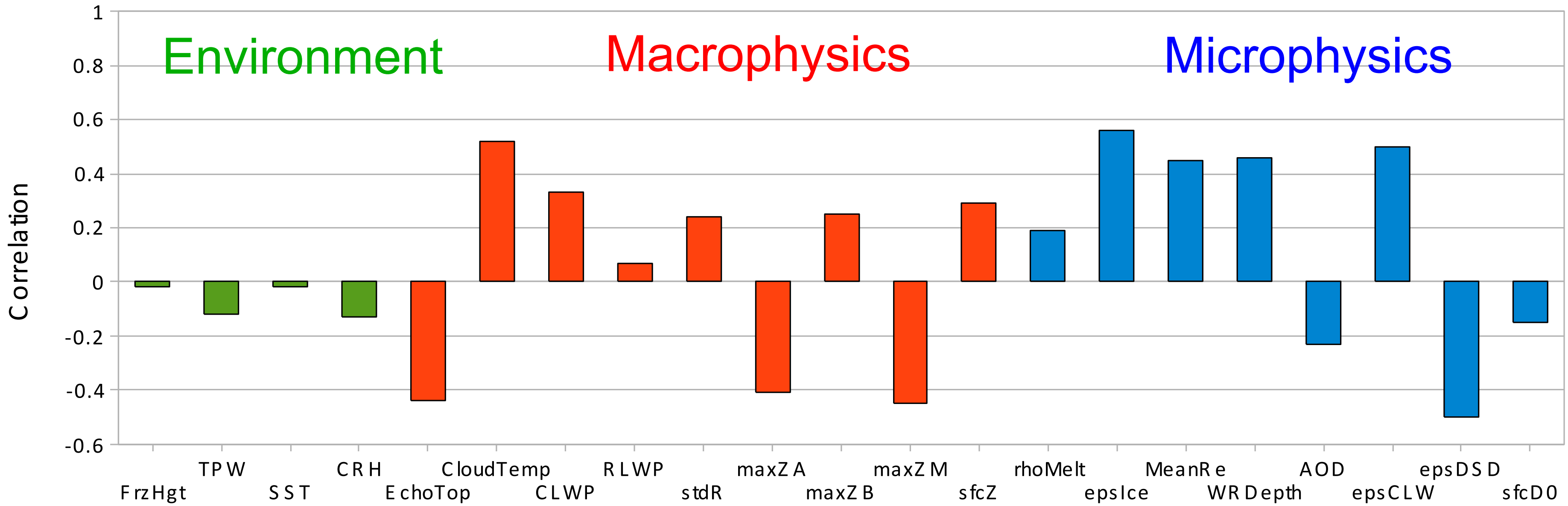
Biases against TRMM Ground Validation (Gauge-tuned Ground Radar) 1999-2004, version 6

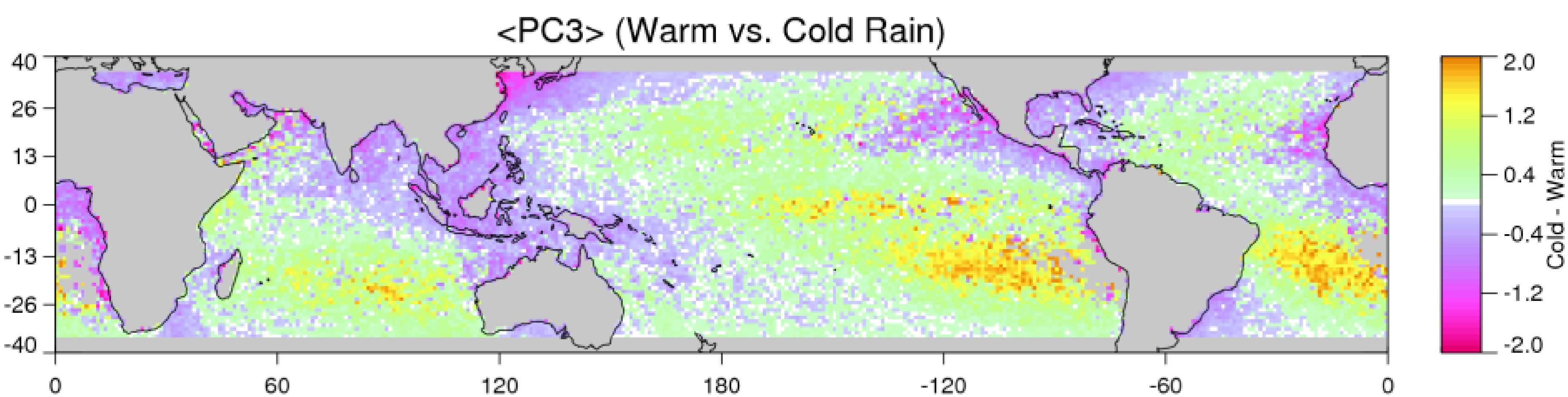
	TMI	PR	COM (2B31)
Kwajalein	-7.9%	-13.7%	-5.7%
Melbourne, FL	-8.2%	+4.1%	+21.3%

Wolff and Fisher (2008)

Courtesy Joe Munchak

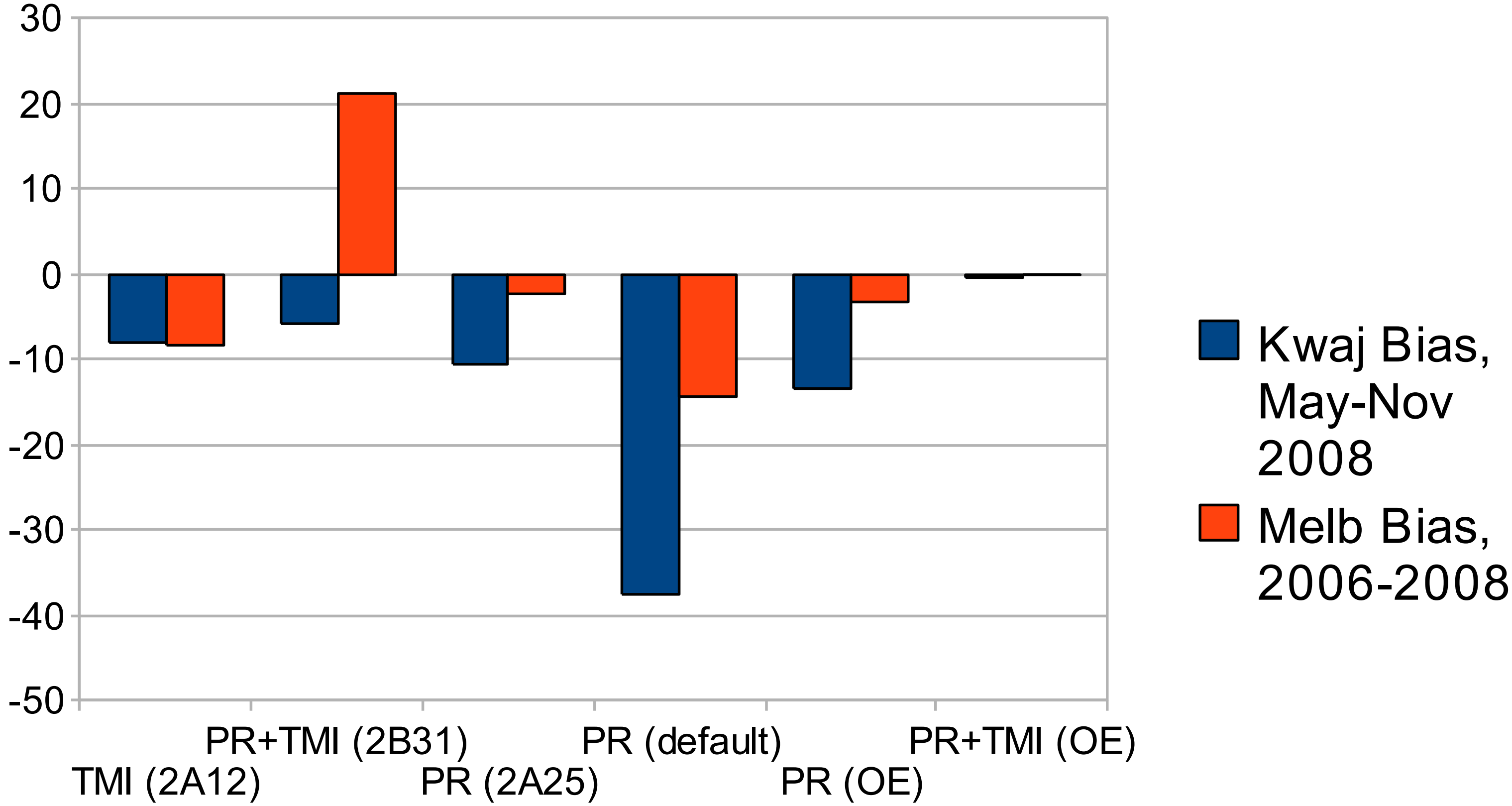
Microphysics Mode





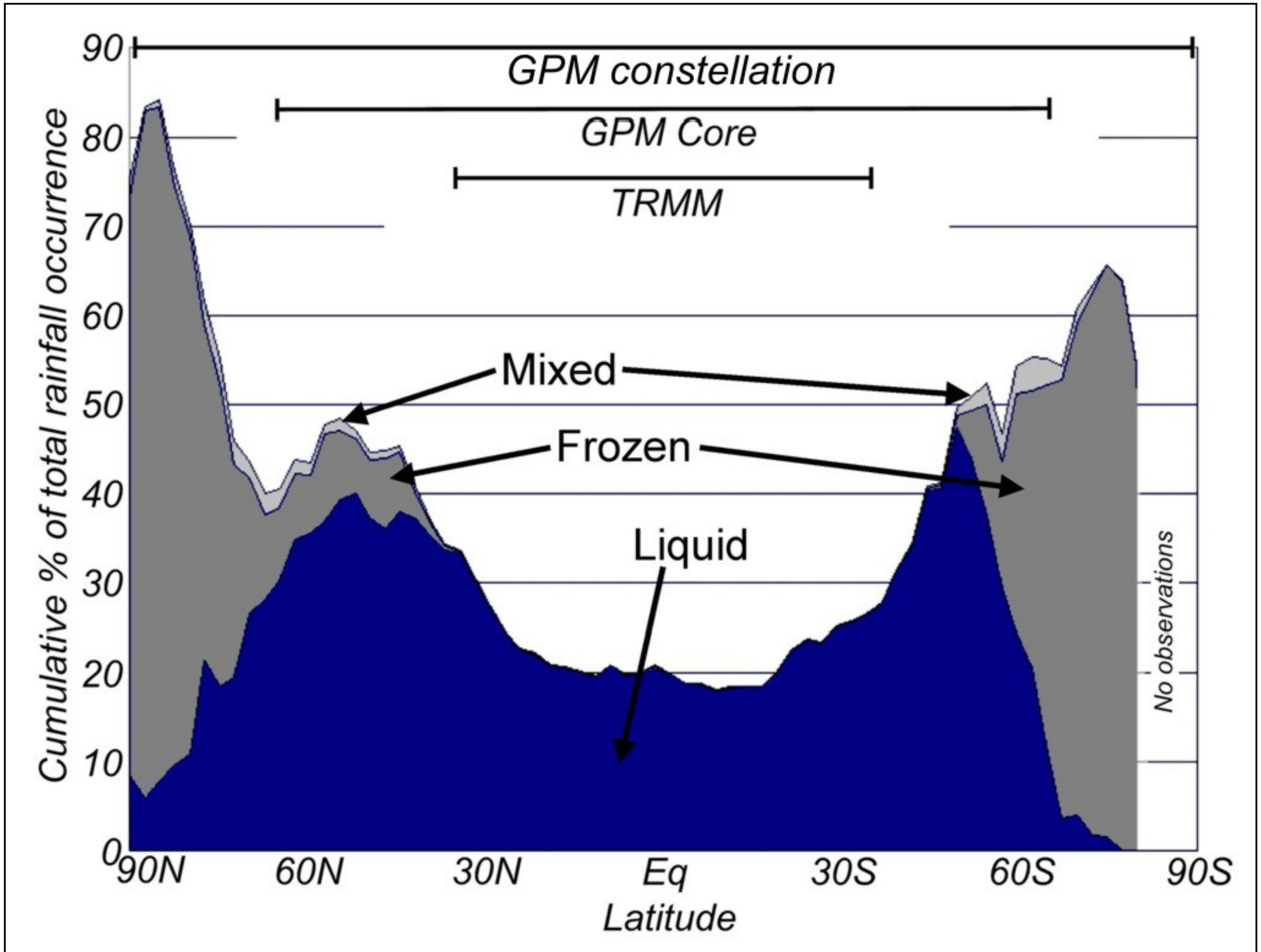
Courtesy Joe Munchak

Back to the original question: **Can a combined algorithm improve upon radar- or radiometer-only product biases in multiple locations?**



What about Light Precipitation?

COADS Observations of Light Precip



Courtesy of Chris Kidd

Contribution of Light Rain
(from Ground-Based Obs.)

PDF of Rainfall Accumulation over the United States

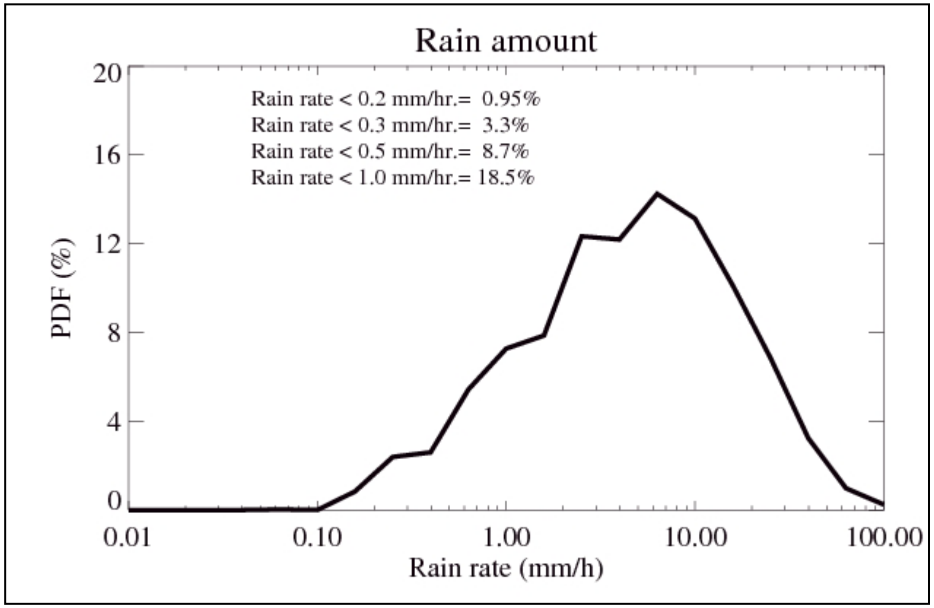


Figure Courtesy of Xin Lin (GSFC)

CDF of Rainfall Accumulation over Europe

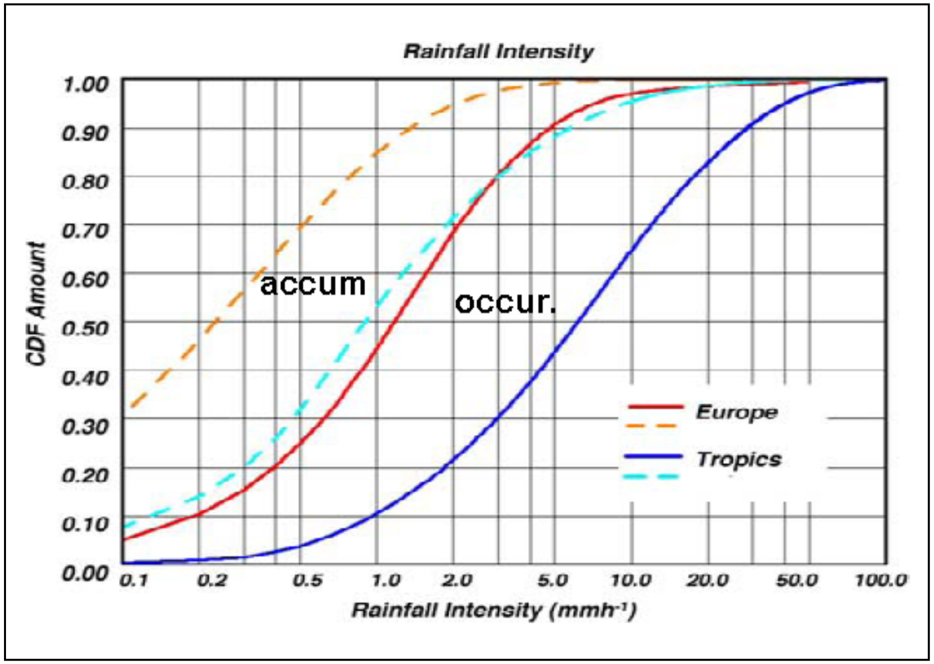
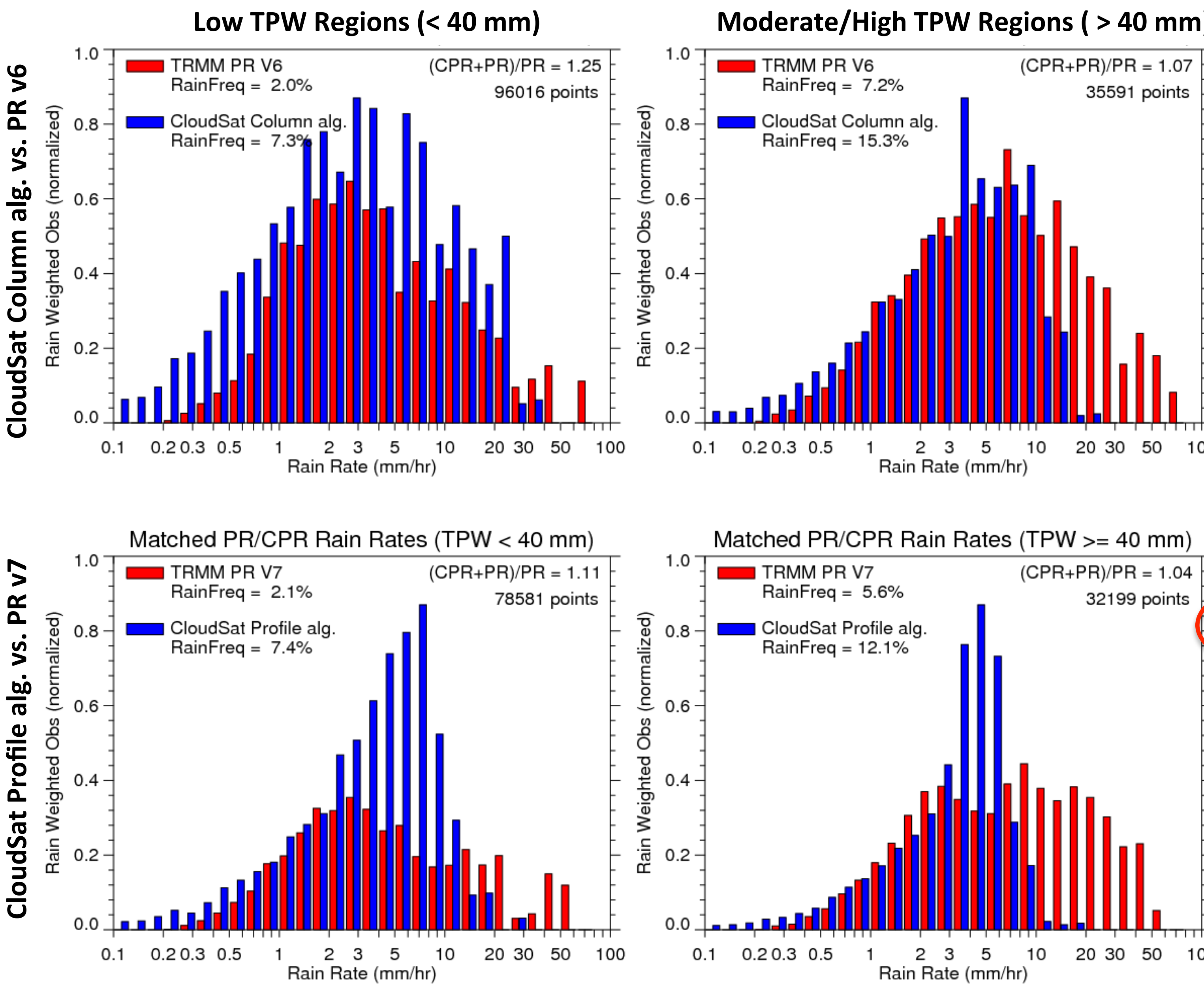


Figure Courtesy of Chris Kidd

Colocated PR and CloudSat Rain Rate Distributions



Rain Volume
- PR misses ~10%

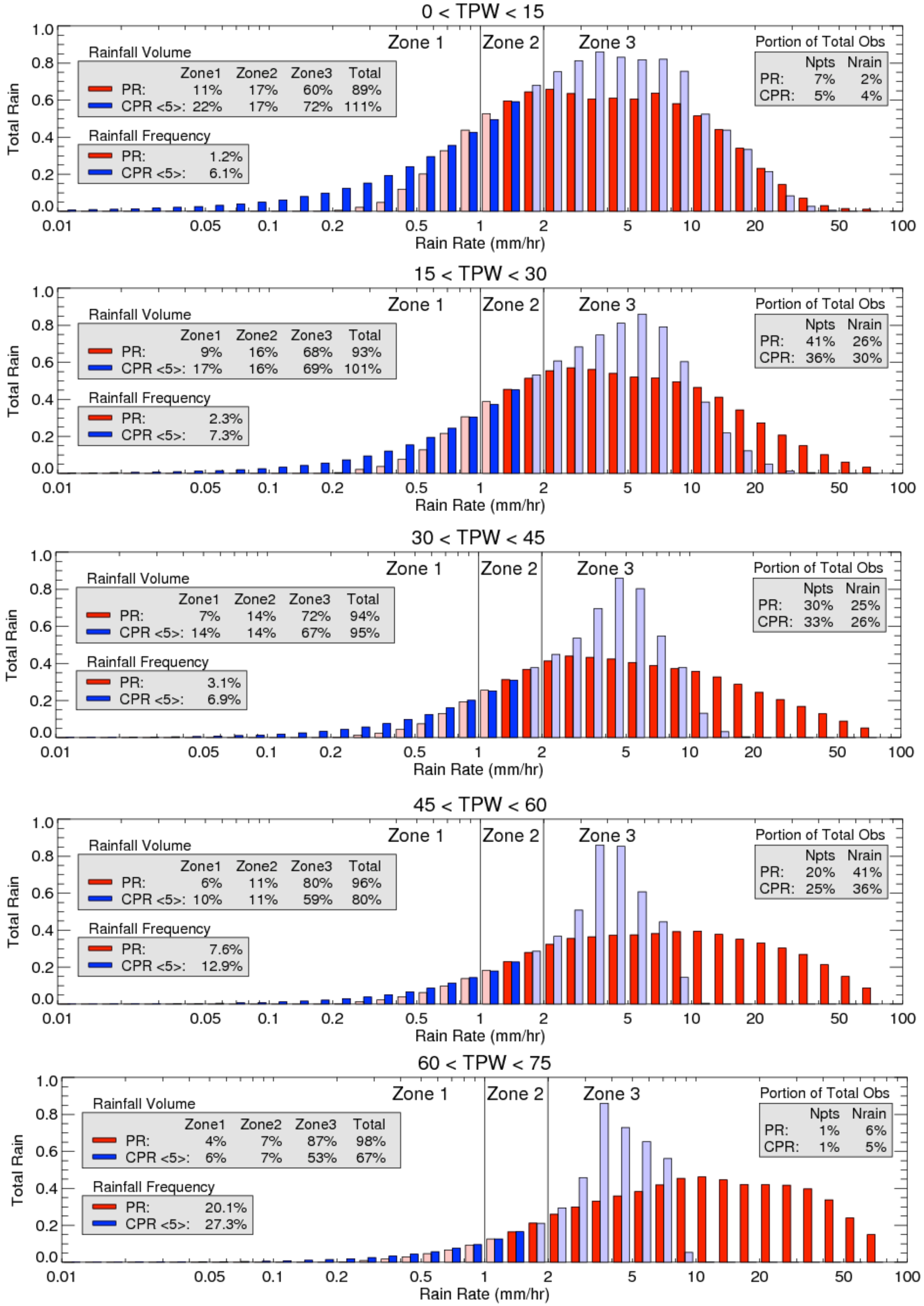
Rain Fraction
- PR -> 3.7%
- CPR -> 8.9%

Rain Volume
- PR misses ~5%

Rain Fraction
- PR -> 3.7%
- CPR -> 8.8%

Good agreement in 1-2 mm/hr range.

PR and CloudSat Rain Rate Distributions vs. TPW



11%

8%

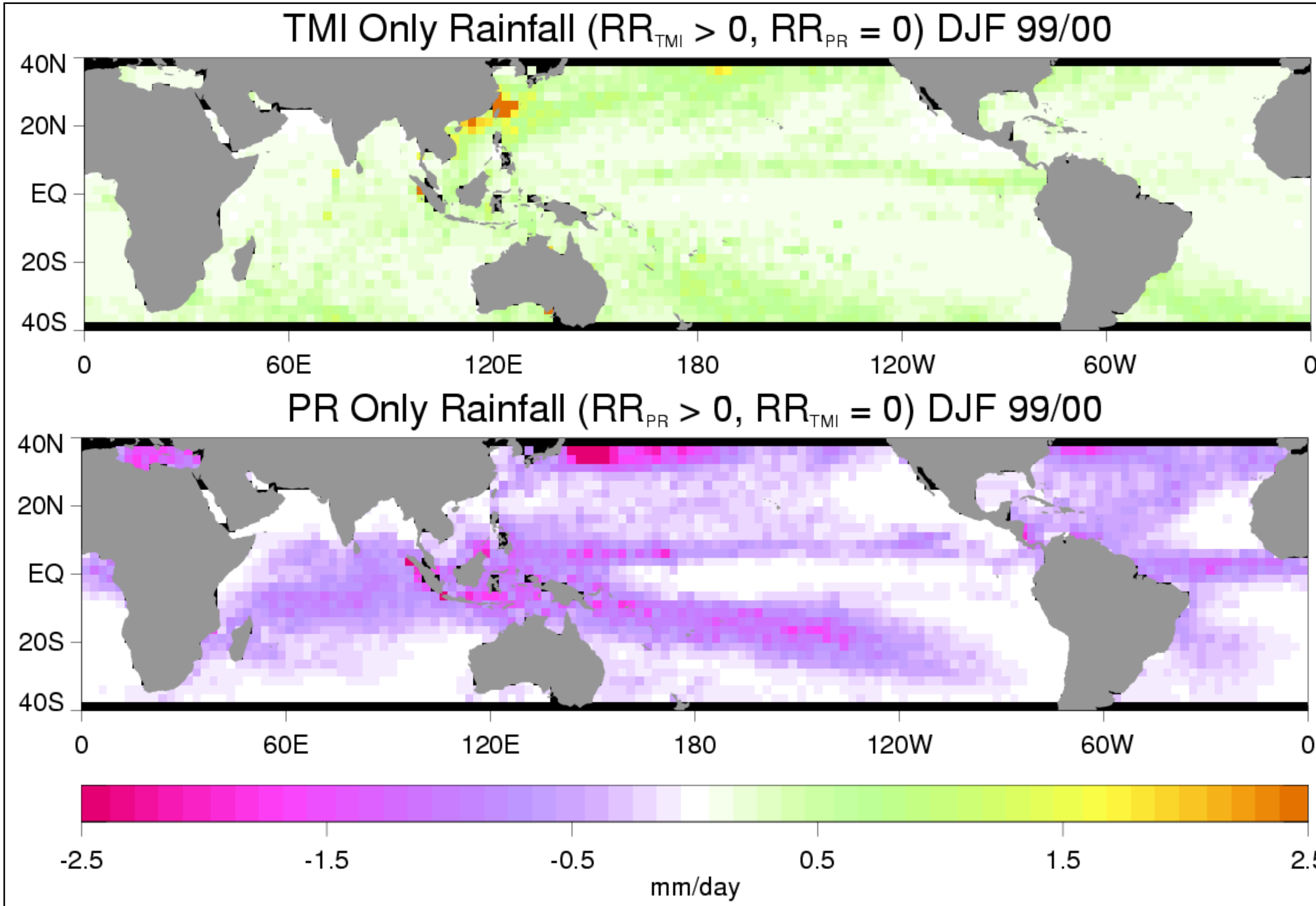
7%

4%

2%

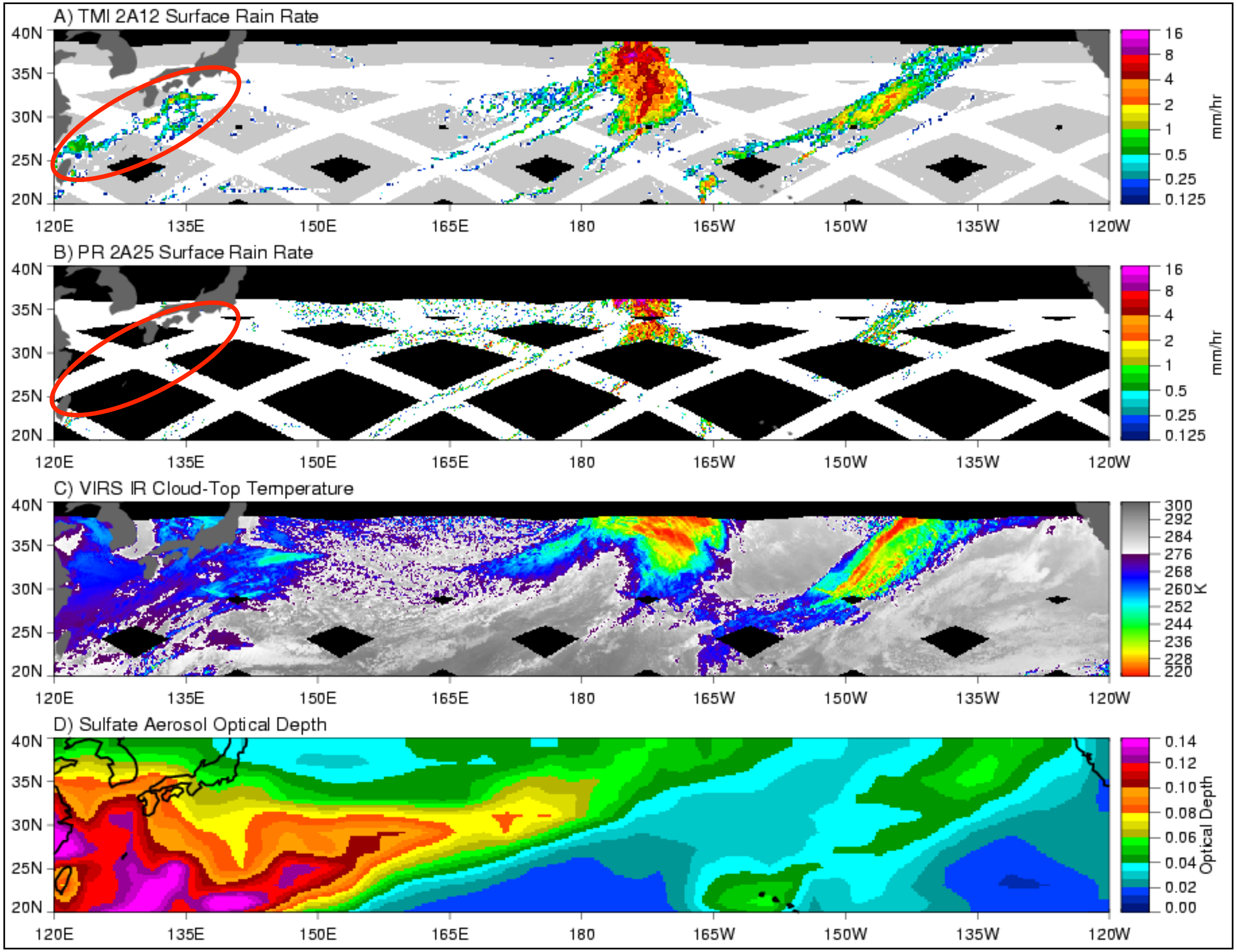
Aerosol Impacts?

TRMM Rainfall Detection Differences



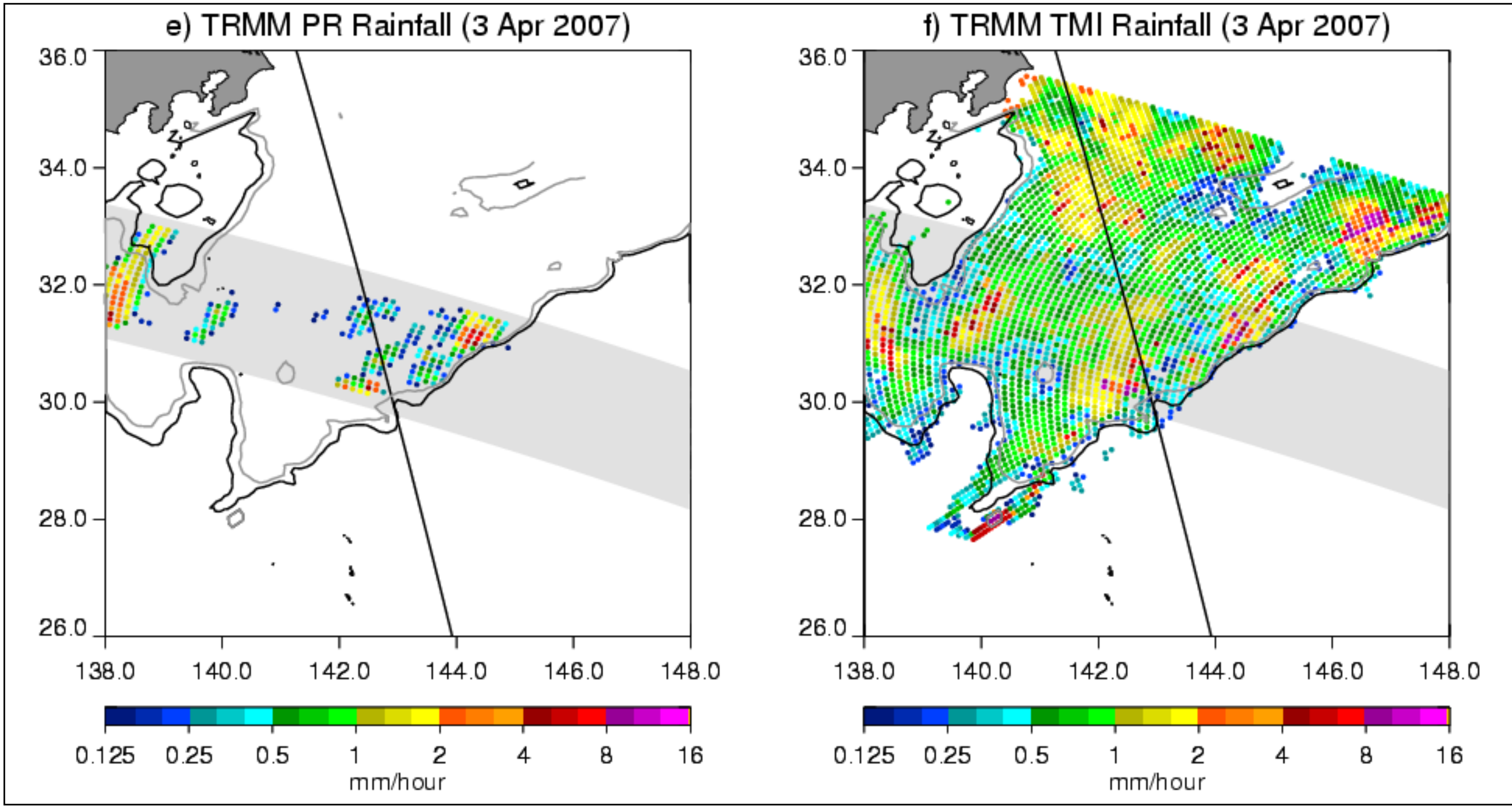
Differences in TRMM Rainfall Detection

February 1, 2000



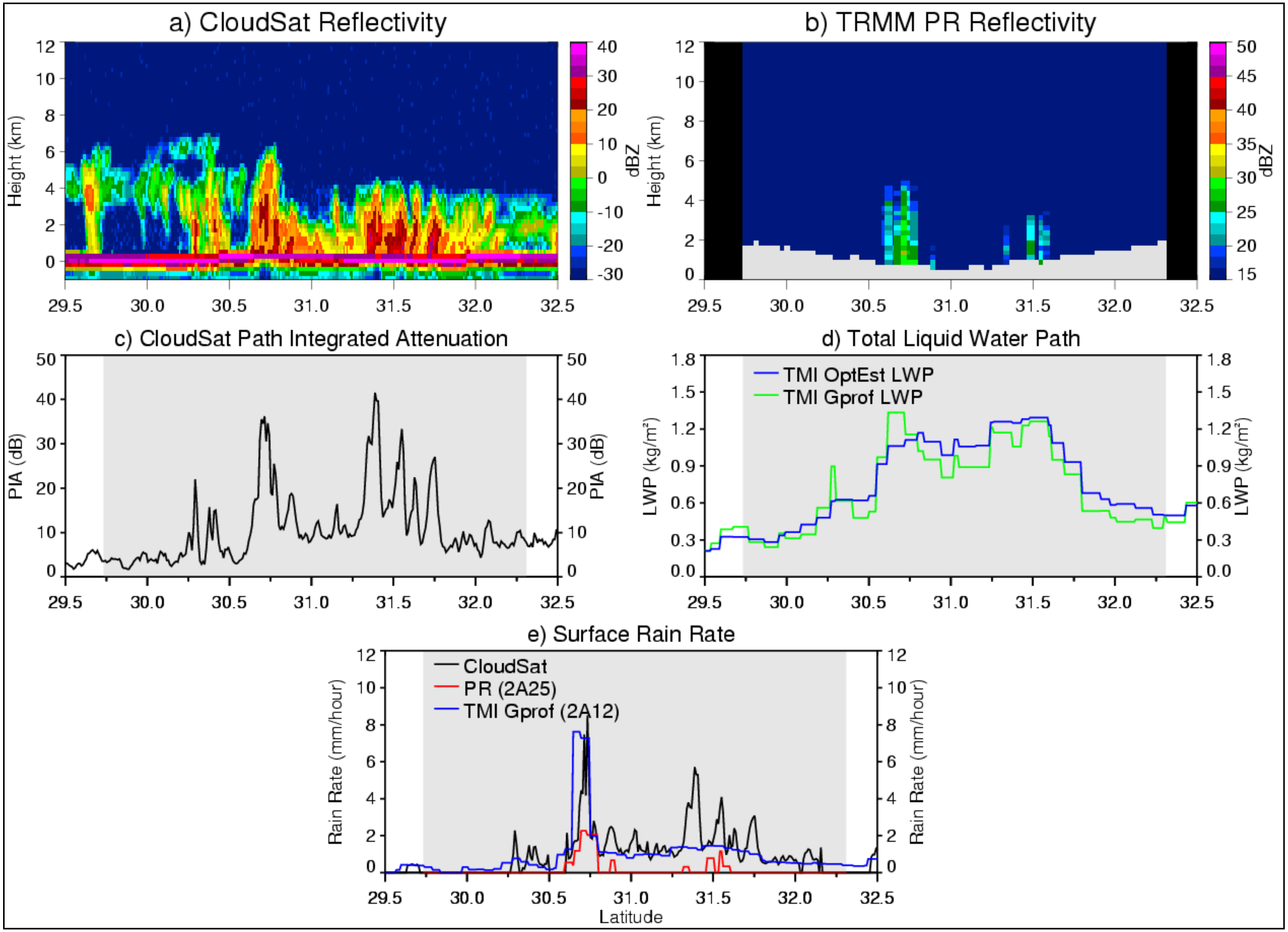
Coincident TRMM/CloudSat Case

3 April 2007



Coincident TRMM/CloudSat Case

3 April 2007



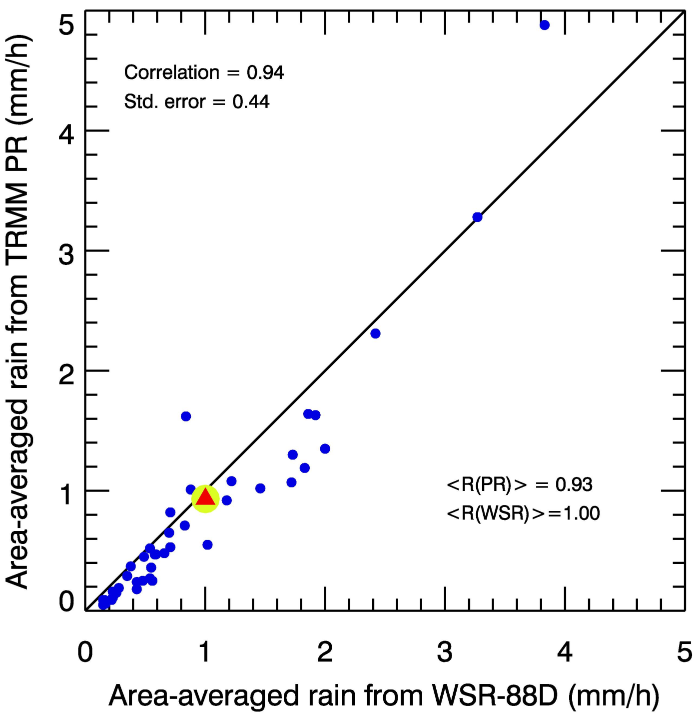
Differences vs. Validation Data

Biases against TRMM Ground Validation (Gauge-tuned Ground Radar) 1999-2004, version 6

	TMI	PR	2B31)
Kwajalein	-7.9%	-13.7%	-5.7%
Melbourne, FL	-8.2%	+4.1%	+21.3%

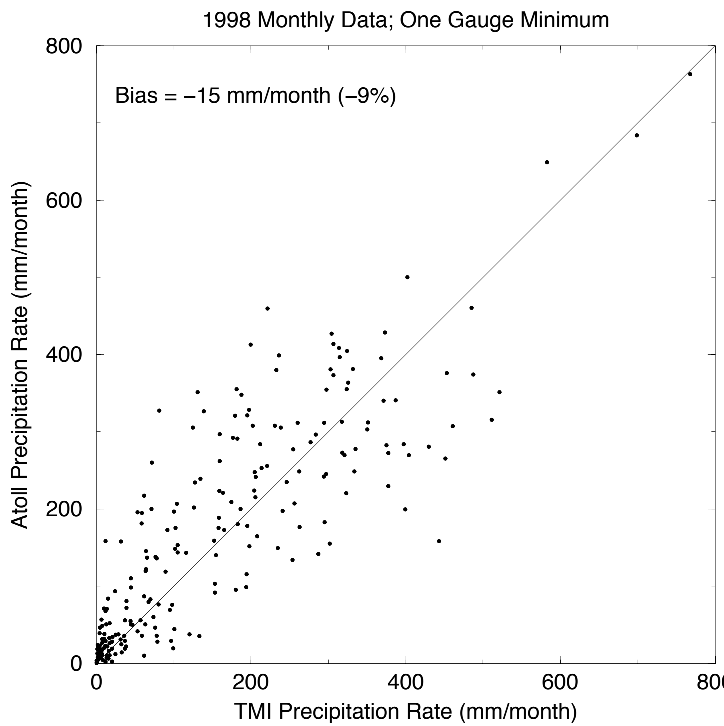
Wolff and Fisher (2008)

- Inconsistent differences between regions/ stations indicates large uncertainties and/or regional bias issues.
- Both PR and TMI appear low vs. ground validation.
- Both PR and TMI global means increased in V7.
- Results generally inconsistent with global mean errors > 10%



Courtesy of R. Meneghini, GSFC

TMI vs. Atolls



Summary

TRMM oceans

- DSD:
  - Due to single frequency PR retrieval, however, more an issue of regional biases than overall global bias.
  - More problematic over land due to noisy attenuation signal.
  - Also affects GPROF 2010 due to use of 2A25 estimates in apriori database.
  - GPM DPR should largely resolve this issue.
- Inhomogeneity and vertical profile issues
  - Largely accounted for with V7 database (uses high-res PR profile info).
  - Inhomogeneity still an issue for PR, but at 5km resolution not a major issue
- Light Precipitation
  - Potentially a significant issue for PR, especially in subsidence regions, higher latitudes etc.
  - TMI is sensitive to both cloud and rain water. Partitioning and inhomogeneity are issues, but likely not the same magnitude. GPROF 2010 is significant improvement over GPROF 2004 in detection of light rain.
  - Increased sensitivity of KaPR should substantially resolve this issue, especially at higher latitudes.

High Latitude Oceans

- Currently GPROF 2010 rainfall significantly drops off at high latitudes due to use of "extended" database.
- GPM core will provide extension of microwave apriori database to 65 N/S.

Land

- A significant issue for current passive microwave retrieval.
- Substantial effort being made to improve retrievals over land, however, poor signal to noise will continue to be an issue.
- GPM DPR will improve both sensitivity and impact of regional DSD variability.

Snow

- Likely to continue to be a significant challenge.

Stephens et al. 2012

Stephens et al. 2012 states "The remote-sensing methods widely used to estimate precipitation, especially over the vast oceans, have documented biases that imply that the amount of precipitation is underestimated. New global precipitation information from the CloudSat radar suggests that precipitation has been underestimated by approximately 10% over tropical ocean regions and by even larger fractions over mid-latitude oceans"

- This likely comes from Behrangi et al. 2012 who conclude that their combined CloudSat/PR estimate is 15– 21% higher than PR and 12– 18% higher than TMI.
- This is not only significantly higher than the estimate of 10% found by Berg et al. 2010, but even more so when compared to the updated results shown here indicating only a 5% difference over the tropics.
- Both approaches use rather questionable assumptions to combine the CloudSat/PR distributions indicating substantial uncertainties with these estimates.
- I find the Behrangi et al. 2012 estimates of light rain contribution difficult to believe, especially considering that TMI is sensitive to light rain.
- Behrangi et al. 2012 also note that their combined CloudSat/PR estimate is only 4-8% higher than that calculated from GPCP. Even this implies that GPCP is probably not dramatically low and are likely quite reasonable in the tropics given that their estimates appear rather high.
- While there are certainly biases in the satellite precipitation estimates as I have shown, the implication that these lead to an overall underestimate ignores the comparisons with available validation data, which often show an underestimate in one place and an overestimate in another.